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APPENDIX E

Modeling 2-Dimensional Unsteady Flow at the Confluence of Riverine and Estuarine Regimes

Modeling 2-Dimensional Unsteady Flow at the Confluence of Riverine and Estuarine Regimes

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Abstract

This paper describes the results of applying a 2-dimensional hydrodynamic model (ADCIRC) to evaluate several alternatives for decreasing the stage of multiple rivers that discharge into a coastal estuary. Reduction of river stage at the mouths of the rivers (in the backbay areas of the estuary) is desirable for reducing inland flooding caused by a backwater effect as the rivers discharge into the estuary.

The project location is Tillamook Bay, Oregon, which is situated on the U.S. Pacific Northwest Coast about 90 miles west of Portland, Oregon. Tillamook Bay is a shallow estuary with complex system of tidal channels and broad inter-tidal mudflats. The estuary receives riverine input from five rivers, all headwatered in the northern Coastal Range of Oregon. A number of narrow channels provide confined pathways for riverine flows entering the estuary from upland sources and the tidal flows entering and leaving the estuary from the ocean. During times of significant upland precipitation/run-off, the hydraulic conditions within the backbay area of the estuary become dominated by riverine flow. The situation becomes a battle of two flow regimes: Riverine vs. Estuarine. The objective of the work reported in this paper was to determine if an estuarine-based channel modification could reduce the water elevation in the back bay area of the estuary during high riverine flow events. Conventional wisdom could lead one to conclude that increasing the conveyance of estuary would reduce stage at the river mouths during a significant riverine flow event. However, based on the results reported herein, estuary-based alternatives are not effective for reducing the stage at the river mouths during a significant riverine flow event. The best method for reducing river stage and alleviate coastal flooding around Tillamook flooding is to (partially) restore the floodway for each of the major coastal rivers discharging into the bay.

Introduction

The motivation for the analysis reported in this paper lies in the chronic flooding that has occurred in the valleys and coastal plains of the Tillamook Bay region (figure 1). The most severe flooding occurs in and around the town of Tillamook. Just downstream of the Tillamook lies Tillamook Bay, a broad and shallow estuary (figures 2 and 3).

The Tillamook Bay estuary is located on the Pacific Northwest coast of Oregon, about 90 miles west or Portland (figure 4). At mid-tide, the estuary is 9 km long (N-S) and 4 km wide (E-W). The average depth of the estuary is about 1.8 m., with respect to mean tide level. The mean tidal range within Tillamook Bay is about 1.7 m.

Five rivers flow into Tillamook Bay. Four of the rivers pass through or nearby the town of Tillamook and flow into the southern end of the bay. During November-April, the town of Tillamook and adjacent areas are prone to flooding due to a backwater effect caused by high flows on nearby coastal streams and elevated water levels of Tillamook Bay. The Wilson and Trask Rivers are the two largest Rivers that flow into Tillamook Bay, and consequently, produce the largest floods. The town of Tillamook largely remains flood free, however, newly developed areas to the north and south of Tillamook experience severe flooding on a regular basis. The worst flooding occurs to the north of Tillamook along a strip of U.S. Highway 101, where flood waters come from the Wilson River, the Trask River, the Tillamook River and from high tides and storm surges in Tillamook Bay. Other coastal plain areas along the Trask, Tillamook and Kilchis Rivers have been historically flooded as well.

The majority of lands in the area are operated as dairy farms and many of the historic dairies are located on high points throughout the area. Many levees have been built in the Tillamook area, most are overtopped during river floodstage and some of the levees are high enough so as to avert overtopping. In either case, the presence of levees along the coastal rivers near Tillamook forces waters to flow through narrow channels, dramatically increasing river stage during high stream flow events. The difference between a river remaining within its banks or spilling over onto the coastal flood plain can be based on the water level at the river's mouth within the Tillamook Bay. If a significant run-off (streamflow) event occurs simultaneously with a spring tide and storm surge event, floodwaters overtop their banks upstream of the levees, resulting in inland flooding.

Climate of the U.S. Pacific Northwest Coast and Flooding at Tillamook Bay

In the northeast Pacific Ocean during winter, weather fronts associated with maritime cyclonic storms can extend over the ocean for 1000's of km and cover a latitude difference of 25 degrees (figure 4). When these maritime low-pressure systems make land fall on the U.S. Pacific Northwest, the coast can be subjected to hurricane-like conditions. The rainfall at coastal locations can be intense and sustained, especially in areas flanked by high relief catchments. Locations at the top of the Oregon Coast Range can receive over 200-inches of precipitation per year while the lowland valleys receive approximately 100-inches per year. Most of the precipitation falls as rain and most falls between the months of October and March. Intense winter storms can produce intense runoff events for coastal rivers. Several of the rivers that drain into Tillamook Bay can experience a rapid change in flow due to winter storm events; increasing from 10 cubic m/s to 300 cubic m/s in a matter of hours.

Offshore Tillamook Bay, wind fields associated with intense winter maritime low-pressure weather systems can create sustained wind speeds greater than 20m/s for fetches greater than 200 km. The resulting wind stress can produce ocean waves greater than 10 m high and a transient “set-up” of the mean water level of 0.3-1.3 m (storm surge for 1-6 hours duration), depending on storm evolution (figure 4).

The Tillamook Bay estuary is a broad shallow estuary with a large number of inter-tidal mudflats and a complex array of inter-connecting tidal channels. Astronomical tides at Tillamook Bay are mixed semi-diurnal; meaning that there are two tide cycles per day of unequal amplitude. The mean tidal range in the lower bay is 1.7 m. The average range of the highest daily tides is the vertical distance from mean lower low water (MLLW) to mean higher high water (MHHW) and is 2.4 m. Extreme tide ranges from –0.9 m MLLW to +3.6 m MLLW. NDVG = +3.0 m MLLW. Tides are modulated by the lunar cycle. During a full or new moon, spring tide occurs (twice monthly) and tide range is larger than average conditions. During half-moon, neap tide occurs (twice monthly) and tide range is smaller than average conditions. The seasonal average coastal water level during winter is 0.2-0.3 meters higher than summer due to dynamics of the northeast Pacific Ocean (figure 4).

The worst set of scenarios for flooding in the Tillamook area occurs in winter (the average bay water level is 0.25 m higher than in summer) when: An intense maritime low-pressure system makes land fall during a spring tide, while the 2 largest coastal streams in the area are near bankfull, and the soil of lowland/upland areas is saturated. This was the case in 1996, when devastating floods struck the Tillamook area.

Use of a 2-Dimensional Model to Investigate Coastal Stream Flooding

Hydraulic connectivity between the Pacific Ocean and Tillamook Bay occurs through a single (entrance) channel located at the northern end of the estuary. During the past 100 years, the entrance channel to Tillamook Bay has been modified by the construction of jetties for navigation purposes. The effect of entrance channel modification has been to transform the estuary entrance from a broad tidal delta to a jettied entrance. The jetties extend about 900 m offshore and act as a nozzle to provide a stabilized inlet that is 300 m wide having authorized navigable depth of 6 meters (figure 2).

Understanding the Problem. It has been alleged that the jetty entrance into Tillamook Bay is more restrictive than the pre-jetty configuration and conveyance of riverine floodwaters (through the estuary) has been reduced. If correct, this process could increase the backwater effect in the backbay area of the estuary, aggravating inland flooding at Tillamook. It has also been stated by local interests that a high degree of sedimentation has occurred within the Tillamook Bay estuary. If correct, this process could reduce the conveyance of river floodwaters out of the bay; adding to the backwater effect and exacerbating inland flooding at Tillamook. Consequently, local interests believed that the best way to alleviate coastal river flooding in the Tillamook area, is to improve conveyance within the estuary by modifying jetty entrance and/or removing sedimentation from the estuary tidal channels; via dredging.

The aggregate area of all 5 catchments that empty into Tillamook Bay is about 1,300 km^2 and the combined 1-yr flow event for peak instantaneous riverine discharge into Tillamook Bay is about 1,110 m^3/s. Under the 1-year flow event (such as the 14 November 2001 event), the cumulative volume of riverine flow into Tillamook Bay during the 24-hr peak of the hydrograph is about 72 km^2-m. The area of Tillamook Bay, as affected by estuarine tidal action, is 37 km^2 and the mean tide range is 1.7 m. On a daily basis, the volume of tidally-driven estuarine water passing through the entrance channel to Tillamook Bay is about 63 km^2-m. For a typical 1-year flow event, the cumulative volume of riverine flow into Tillamook Bay during the 24-hr peak of the hydrograph is (15%) greater than the volume of tidally-driven marine water that enters and leaves the estuary. Given the 1+:1 ratio of riverine flow during the 1-yr event vs. normal estuarine tidal flow capacity, it appeared that Tillamook Bay may not have the "reserve" conveyance necessary to avert a backwater situation at the river mouths during significant riverine flow events.

The above considerations indicated that improving conveyance of flow through Tillamook Bay estuary could alleviate the flooding of Tillamook and surrounding areas. Evaluating the interaction of coastal and riverine flow regimes within an estuary as complex as Tillamook Bay required a robust 2-dimensional approach.

Modeling Approach. The intent of the modeling activity was to first perform calibration-validation activities to a reasonable level of accuracy (+- 0.2 m), then evaluate the water level (stage) within the back bay of the estuary based on specific 1-year flow event, for existing conditions. In effect, modeling was performed at a reconnaissance level of accuracy. After simulating existing conditions within the back bay, the model was used to assess several alternatives for increasing the conveyance of riverine flow through the estuary. Alternative results were compared to the existing conditions. If the estuary "conveyance" alternatives reduced the stage within the back bay during the peak of the 1-yr flow event (as compared to the present condition), then it could be concluded that inland flooding was related to Tillamook Bay flow characteristics. It would follow that increasing conveyance within the estuary could reduce inland flooding near Tillamook.

If the model showed that the estuary "conveyance" alternatives did not reduce the stage within the back bay during the peak of the 1-yr flow event (as compared to the present condition), then it could be concluded that inland flooding was not related to conveyance issues within Tillamook Bay. If this scenario proved true, it would follow that the only feasible way to reduce riverine flooding inland from Tillamook Bay would be to change to hydraulic characteristics of the rivers and associated floodways.

Alternative Formulation - Estuary Conveyance Modification

To test hypotheses advanced in the previous section, several alternatives were developed to modify the conveyance of flow through Tillamook Bay estuary. The premise being, modification of the estuary conveyance will result in modification of stage at the river mouths into the estuary. The "conveyance alternatives" focused on modifying flow through the ocean entrance to the estuary or through the center channel of the mid-estuary. Specific alternatives for increasing estuary conveyance included:

A. Modifying the **<u>ocean entrance</u>** channel into the bay. Enlarging the ocean entrance to Tillamook Bay by removing 100+ m of Kenchloe Point & deepening the jetty entrance channel to –11 m NGVD (figure 5),

B. Modifying the central **tidal channel** through the bay. Enlarging the width (to 200 m) & deepening (to –2 m NGVD) the central tidal channel through the estuary (figure 5),
C. **Combine** both A and B, and
D. **Restricting tidal flow** into the bay. Filling-in the jetty entrance channel at the ocean entrance to the estuary to -2 m NGVD (the opposite of alternative A).

The above alternative plans could be considered by some to be radical, due to the extent of estuary modification that would be required to implement each alternative. If there is a hydraulic effect due to any one of the alternatives, then it should be easily observable within the model. This would give a clear indication if riverine flooding is (or is not) due to an estuary effect and whether an estuarine-based alternative exists to reduce riverine flooding. This is one reason why numerical modeling is so useful; to investigate scenarios that would otherwise be impossible to assess without first building a physical model or prototype. Each alternative was adapted to a computational grid on which the hydrodynamics of the estuary were simulated for a specific storm event using the ADCIRC model. The same was done for the baseline (present) condition. A consistent grid was used to simulate hydrodynamics for the baseline and alternative conditions, to permit unbiased comparison.

ADCIRC Hydrodynamic Model

The ADvanced CIRCulation (ADCIRC) numerical model was chosen for simulating the long-wave hydrodynamic processes in the study area. By specifying the tidal-elevation signal at the ocean boundary, the wind-induced shear stresses over the model domain, and riverine flow, the ADCIRC model can simulate time varying circulation (water velocity and stage) throughout Tillamook Bay. The ADCIRC model was developed in the USACE Dredging Research Program as a family of two- and three-dimensional finite element-based models (Luettich et al. 1992). Model attributes include the capability of:

A. Simulating tidal circulation and storm-surge propagation over large computational domains while simultaneously providing high resolution in areas of complex shoreline and bathymetry. The targeted areas of interest include continental shelves, nearshore areas, and estuaries.

B. Representing the pertinent physics of the equations of motion. These include tidal potential, Coriolis, and all nonlinear terms of the governing equations.

C. Calculating reliably and efficiently over time intervals ranging from days to years.

In two dimensions, the model formulation is based on the depth-averaged finite amplitude non-linear equations for conservation of mass and momentum. The formulation assumes that water is incompressible and barotropic, and that the pressure is hydrostatic. Rather than directly solving the Navier-Stokes and continuity equations, ADCIRC employs the Generalized Wave Continuity Equation (GWCE) for computing water-surface elevations and velocities. The GWCE-based solution scheme eliminates several problems associated with those finite-element schemes that solve the primitive forms of the continuity and momentum equations, including spurious modes of oscillation and artificial damping of the tidal signal. Forcing functions can include time-varying water-surface elevation, wind shear stress, atmospheric pressure gradient, and riverine input. The Coriolis force is included in the GWCE. Also, the study area can be described in ADCIRC through either a Cartesian (flat earth) or spherical coordinate system.

The ADCIRC model is based on a finite-element (FE) algorithm for spatially solving the GWCE over complicated bathymetry encompassed by irregular sea, coastal, and estuarine boundaries. The FE algorithm allows for flexible spatial discretization (grid generation) over the computational domain while retaining high stability. The advantage of this flexibility in developing a computational grid is that larger elements can be specified in open-ocean regions where less resolution is needed.   Smaller elements can be specified in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details (in channels, around islands, and tidal flats). ADCIRC can also simulate wetting and drying of tidal flats, which was a crucial for successful modeling of estuarine flow in Tillamook Bay.   The GWCE is solved in time using an implicit Crank-Nicholson finite difference scheme. As with any numerical model that uses a “grid” to descretize the real world for computation, proper development of the model grid is the key to successful problem formulation and solution generation.

ADCIRC Computational Grid

In multi-dimensional finite element modeling of geophysical flow, a study area is defined by means of an unstructured grid composed of triangular elements to represent the terrain of interest (x,y,z). Elevation (bathymetry or topography, z) is specified at the vertices (x,y), referred to as nodes, of each element composing the grid. The time-varying water surface elevations and the horizontal velocities are computed at the nodes. Figure 6 shows the computational grid developed for this study. The Tillamook Bay estuary consists of numerous tidal flats and narrow channels. The grid was designed to carefully represent all the channels and tidal flats of the estuary. To prevent inadvertent drying of the tidal channels by the model, a minimum of three elements was required across the channel width. Numerical stability considerations limit the smallest size that the elements can get while keeping the time step within computationally feasible limits. The time step used for applying ADCIRC on the Tillamook Bay grid featured in this paper was 2 seconds. For an 8-day simulation on the subject grid, the ADCIRC model ran in about 10 hours on an Intel pentium-4 PC.

The computational grid featured in this paper encloses Tillamook Bay entirely and includes an idealized representation for the lower 1-3 km of each of the fives rivers flowing into the bay. The open-ocean boundary of the grid is situated a considerable distance (300-500 km, figure 4) from the project area to facilitate the proper generation of the tidal signal from the imposed tidal boundary-condition and allow proper development of coastal current from the imposed wind-field. The computational grid for the Tillamook Bay application consists of roughly 12,400 nodes and 23,000 elements. The largest elements reside along the western (ocean) grid boundary where nodal spacing is about 80 km. Smaller element sizes (about 20 m) are specified for resolving the tidal channels inside the bay. Grid development involved several iterations of model simulations and many grid modifications. In this application, the grid was *edited* in Cartesian coordinates (NAD27 SPCS Oregon North and NGVD, m) and the model was *run* with the grid in the spherical coordinate system (NAD 27 and NGVD, m).

Elevation and shoreline data used to generate the ADCIRC grid for the Tillamook Bay modeling effort was obtained from three sources. In the vicinity of the jetty entrance, bathymetry data was obtained in 2000 using a multibeam fathometer (data reported at 2 m intervals). Bathymetry for most of the estuary was compiled from conventional fathometer soundings conducted in 2001 (data collected at 3 m intervals along variable transects). Topography of mudflats was compiled from a controlled aerial survey conducted in 2001. Tidal channels in the back bay were surveyed during 2000-2001 using fathometer and land-based methods. Oceanographic bathymetry beyond the project area was obtained from a NOAA digital database. All survey data was compiled into a common ASCII (x,y,z) file, which was interpolated onto the ADCIRC grid (figures 3 and 5). Depths assigned to grid nodes were found by interpolating the three nodes contained in the database that encloses a given grid node. Nodal depths are interpolated with an algorithm that weights each sounding or data point inversely proportional to its distance from that node.

ADCIRC Model Simulations

During the process of establishing a numerical model to represent a given study area, calibration is performed to ensure the model adequately predicts hydrodynamic conditions. Accuracy of a model is determined by the accuracy of the boundary and forcing conditions, representation of the geometry of the study area (i.e., bathymetry and land-and-water interface), and, to a lesser extent, by the values of certain parameters, principally the bottom-friction coefficient. A satisfactory comparison between ADCIRC simulations and measurements in the calibration procedure gives confidence that the model adequately simulates hydrodynamic processes. Calibration and validation exercises were conducted via comparisons of water surface elevations (stage) calculated with the model to those measured within the domain.

The intent of this modeling effort was not to reproduce the exact water surface elevation (stage) *within the rivers* that drain into Tillamook Bay. Rather, the ADCIRC modeling effort focused on accurately reproducing stage within the estuary and backbay areas, and to qualitatively reproduce stage at the river mouths. When conveyance modifications were made to the estuary, it was deemed important to accurately depict the associated changes within the estuary. In this regard, “qualitative” estimates of river stage for the baseline and alternative plans could be compared with a reasonable level of certainty.

Model simulations were conducted for two times periods (Chawla 2002). In the first case (calibration), the forcing environment within Tillamook was dominated by tidal action; there was very low river discharge and no wind forcing (storm surge). The aim was to test how well the tidal oscillations are simulated by the ADCIRC model. In the second case (validation), the time period centered around a storm event which was accompanied by strong wind conditions and higher levels of river discharge into the estuary.

Observed Data. USACE-Portland District maintains 5 tidal gages inside the estuary (USACE 2003). Stage data from these gages was used to calibrate the Tillamook Bay ADCIRC model. The Garibaldi gage is located within 3 km of the ocean entrance to the bay and its hydraulic response is dominated by the ocean conditions at the mouth of the estuary. The remaining 4 gages were located further upstream to observe the stronger influence of river discharge on water surface elevation (WSE) data. The gages at Garibaldi, Dick Point, Wilson River, and Kilches River were used to validate the ADCIRC Tillamook Bay model (figure 6). Stage data was synchronously recorded at each gage using a 15 minute interval, in NAVD (0 NAVD = -1.036 NGVD). It is noted that during fall 2001, the Tillamook Bay stage gages had problems dealing with power fluctuation, hysteresis, and creeping datum offset. Other data use to specify model boundary conditions during model validation included wind field data (6 hour sampling interval) and riverine flow data (30-minute sampling interval, figure 7).

Calibration Run. The hydrodynamic model was calibrated by adjusting the bottom-friction and lateral diffusion (eddy viscosity) coefficients so that model-generated WSE time-series compare favorably to observed values. If needed, the computational grid was modified to resolve complex flow interactions. Calibration was based on a tidal flow test case was run for a 15-day simulation extending from 04/14/2001 to 04/29/2001. The run had a 5-day ramp-up period, which is included in the 15-day simulation period. The river discharge during this period was very low and thus the river boundaries were treated as closed boundaries for this test case. No winds were forced for this run. The only forcing on the ADCIRC model was due to tidal potential, which was applied along the offshore open boundary. During calibration, considerable effort was expended to refine the grid in the estuary entrance and back bay areas to capture the hydraulic connectivity of narrow tidal channels. Vast inter-tidal areas (mudflats) where topographic & bathymetric gradients are gradual and tidal excursion causes wetting and drying, were particularly troublesome for maintaining model stability. To address these issues, the computational grid was modified to eliminate ponding within mudflats, ambiguous terrain gradients. The orientation of grid elements (connectivity) was improved, to conform the grid to mudflat and tidal channel contour alignment. Collectively, these grid modifications significantly improved model results as compared to initial calibration runs.

The model simulations were found to be stable for time steps no greater than 2 seconds. This limitation is due to the numerical restrictions placed on the model by the smallest elements in the grid. The numerical solutions were found to be unstable for values of lateral diffusion greater than 1 to 5 m^2/s, depending on the value of other model parameters. This is contrary to conventional expectations, where an increased lateral diffusion would be expected to decrease instability. It is hypothesized that inside the narrow channels of the estuary, the lateral diffusion was having a negative impact by spreading the noise in the flow field into the much shallower tidal flat region, where the noise was amplified instead of being suppressed (Chawla 2002). Based on the final calibration runs, WSE for the ADCIRC model was within 0.2 meters of observed values, and performed reasonably well in simulating tidal flow conditions in the Tillamook estuary. Chawla (2002) describes calibration results in detail.

Validation Run. The emphasis of the work described here centers on replicating the stage within the Tillamook Bay during a spring tide event when there is considerable riverine flow and coastal storm surge. Such an event occurred on 14 November 2001 and is featured in this paper. The ADCIRC model was run for an 8 day simulation, including a 1 day ramp-up period, beginning at 08:00 9 November 2001 GMT. The storm peak conditions occurred on day 5 of the ADCIRC simulation. The model simulated WSE at the gage locations (figure 6) every 15 minutes during the 8 day run.

Several changes were made to the model to improve performance and allow specification of additional boundary conditions for the time-varying wind field and riverine input. Due to the large excursion of WSE during the validation run (superposition of spring tide, storm surge, and riverine flow), the model parameterization for bottom shear stress was changed for the validation run; a hybrid nonlinear bottom friction law was used. In deep water, the friction coefficient is constant and a quadratic bottom friction law results. In shallow water the friction coefficient increases as the depth decreases (e.g. as in a Manning-type friction law). The friction factor (Cf) varied such that in 0.05 m water depth Cf = 0.06, in 4 m depth Cf = 0.004, and in 10 m depth and greater Cf = 0.0025. The eddy diffusivity coefficient was set to a global value of 3 m^2/s.

Forcing mechanisms specified in the model include tide, tide-generating potential, river discharge, and the Coriolis force. Time-varying tidal elevations specified at nodes along the open ocean boundary were synthesized using eight tidal constituents: M_2, S_2, N_2, K_1, O_1, Q_1, P_1, and K_2 (obtained from the LeProvost data base). Because the model domain is of sufficient size that celestial attraction induces tide within the grid proper, tide-generating potential functions were included in the simulation calculations, and these functions incorporated the above listed eight tidal constituents. The wind field data supplied to the model was extracted from the NCEP database. Wind fields were input into the model having the spatial resolution of 2.5 deg longitude by 2.5 deg latitude and 6-hr intervals, as archived in the database. A snapshot of the time varying wind field is shown in figure 7. Maximum sustained wind speed during the storm was 21 m/s. Time-varying riverine flow was input to the model along the upstream boundary for each of the bay's 5 rivers (figures 3 & 6). Peak river flowrate observed during the storm was 430 cm/s (Wilson & Kilches Rivers).

Figures 8 & 9 compare ADCIRC <u>model</u> and <u>observed</u> values for WSE at four gage locations within Tillamook Bay (figure 6), for the "existing condition" bathymetry. Overall, there was little phase difference between the ADCIRC model and observed WSE. Model-generated peak values of WSE within the estuary are generally within 0.2 m of observed values. Note that during the storm, the model-generated WSE is about 0.1 to 0.2 m lower than observed values throughout the estuary; and was likely due to the model under predicting storm surge on the coast. This was to be expected, since the wind forcing data was deemed sufficient to reproduce the general effect of storm surge, but not detailed enough to produce exact results. In the riverine reach of the Wilson River (figure 9 upriver of the mouth) where riverine flow controlled WSE during the storm, model results during the storm do not attain the same level of peak values as the observations show.   This was due to inadequate grid resolution and geometry description of the Wilson River and was expected due to the schematized representation of the rivers within the computational grid. Note that the tidal gages at Kilchis Cove and Wilson at Geinger came out of the water during low tides. This explains the cutoff in the tidal signals of these gages during low tides. During fall 2001, several of the stage gages were affected by low power supply and hysteresis (notably Dick Point) rendering exact comparison to the ADCIRC model problematic. In general, the model results agree with observations to an adequate level such that confidence was established in the model to reliably describe WSE throughout the estuary during a "storm" for the present configuration.

Alternative Runs. At the time of model validation, the computational grid for the existing condition of Tillamook Bay was modified to allow consistent grid definition (and comparison) for all alternatives. This meant that the same grid geometry (x,y) was used for all model runs. The four alternatives were represented within the grid by changing elevation (z) values at spec nodal points. Alternatives were focused on modifying hydraulic conveyance through the Tillamook Bay's jettied entrance and central part of the bay. Refer to section "Alternative Formulation - Estuary Conveyance Modification" for additional details.

Figure 10 compares ADCIRC results for the "existing condition" and alternatives (A, C, and D) at two gage locations within the back bay area of the estuary: At the Wilson River and Kilches Cove (figure 6). Results for the other locations and alternative B are omitted here for brevity. At first glance, the results appear confounding; but such is the case in tidal hydraulics. Despite the massive geometry changes associated with alternatives A and C, there is little change in peak WSE at any of the gage locations.   Apparently, the present estuary condition is not "choked" and is near maximum efficiency for conveying a spring tide with the 1-year riverine flow event. This means that no reasonable level of estuary modification can increase conveyance of water through the estuary, such that the WSE within the back bay area of the estuary is reduced from its present high tide level.   There is a small, but notable difference between alternatives A and C during low (ebbing) tide at the Wilson gage (top graph, figure 10). During low river flow, alternative C conveys the ebb tide out of the estuary back bay (Kilches Cove) more efficiently than the "existing condition" or alternative A (or B). During high river flow, alternative A conveys the ebb tide out of Kilches Cove more efficiently than alternative C (combined entrance deepening + central channel deepening). This is due to the deepened central channel (alternative B and C) modifying the ebb tide flow in Kilches Cove resulting in higher frictional effects and high stage at that location (during lowtide).

The concurrence of high river discharge on a high spring tide is the process that drives flooding in the Tillamook area: A high spring tide causes a backwater effect at the mouths of rivers discharging into Tillamook Bay. Aggressive modification of the estuary's channels will increase conveyance of estuarine water flowing *into and out* of the bay. Increasing the conveyance of floodwaters out of the bay is desirable, and will result in lowering of WSE during ebb (or low) tide. Decreasing the low tide WSE is not of primary concern; it is the WSE during high tide that causes problems. However, increasing the conveyance of estuarine water flowing into the bay will increase the WSE during flood (or high) tide. This is obviously not desirable. This is basically what alternative A-C did. Alternative D was intended to restrict the conveyance of marine water flowing into the bay, thus reducing WSE during high tide. Reducing conveyance would also have the effect of increasing WSE during ebb (low) tide. Figure 10 (dashed line) shows the result of running ADCIRC with a filled entrance channel (to –2 m NGVD). During low river flow conditions, alternative D had a significant impact on WSE at all of the gage locations, acting to reduce high tide WSE by more than 1 meter. During high river flow conditions, alternative D had little effect on high tide WSE in the back bay areas or at the river mouths in Tillamook Bay. This final result confirmed the following conclusion: Inland flooding at Tillamook was not related to conveyance issues within Tillamook Bay. The only feasible way to reduce riverine flooding inland from Tillamook Bay is to change to hydraulic characteristics of the rivers and associated floodways.

Conclusions

Using even a robust numerical model to simulate hydrodynamics within Tillamook Bay proved to be challenging when confronted with: constricted riverine geometry producing rapidly varying flow that exceeds 2 m/s, a semi-diurnal tide of 2.4 m within the estuary, broad mudflats which are wetted and dried during each tidal cycle, a complex system of interconnecting tidal channels, estuarine flow through the estuary's jettied entrance (to the ocean) exceeding 2 m/s, and a transient water level set-up due to strong wind forcing. Considerable effort was expended to conform the highly irregular bathyemtry of Tillamook Bay onto a numerical grid, to ensure stability for numerical modeling. The ADCIRC model produced acceptable results despite these handicaps, but the model was applied to its practical limit with respect to maintaining numerical stability within the backbay of the estuary.

Based on the results described in this paper, inland flooding near the town of Tillamook is not related to conveyance issues within Tillamook Bay. The only feasible way to reduce riverine flooding inland from Tillamook Bay is to change to hydraulic characteristics of the rivers and associated floodways.

Lessons learned include the following observations: It is essential to accurately resolve complex bathymetry of an estuary when simulating unsteady flow using a 2-D hydrodynamic model; Increasing the diffusion coefficient in a numerical model can increase instability; Use a spatially-variable friction factor is required to properly simulate 2-D flow within an estuary; Before calibrating/verifying a numerical model, ensure that the prototype data is accurate and consistent for the time period of interest; A numerical model can be used to assess the accuracy of prototype gage data.

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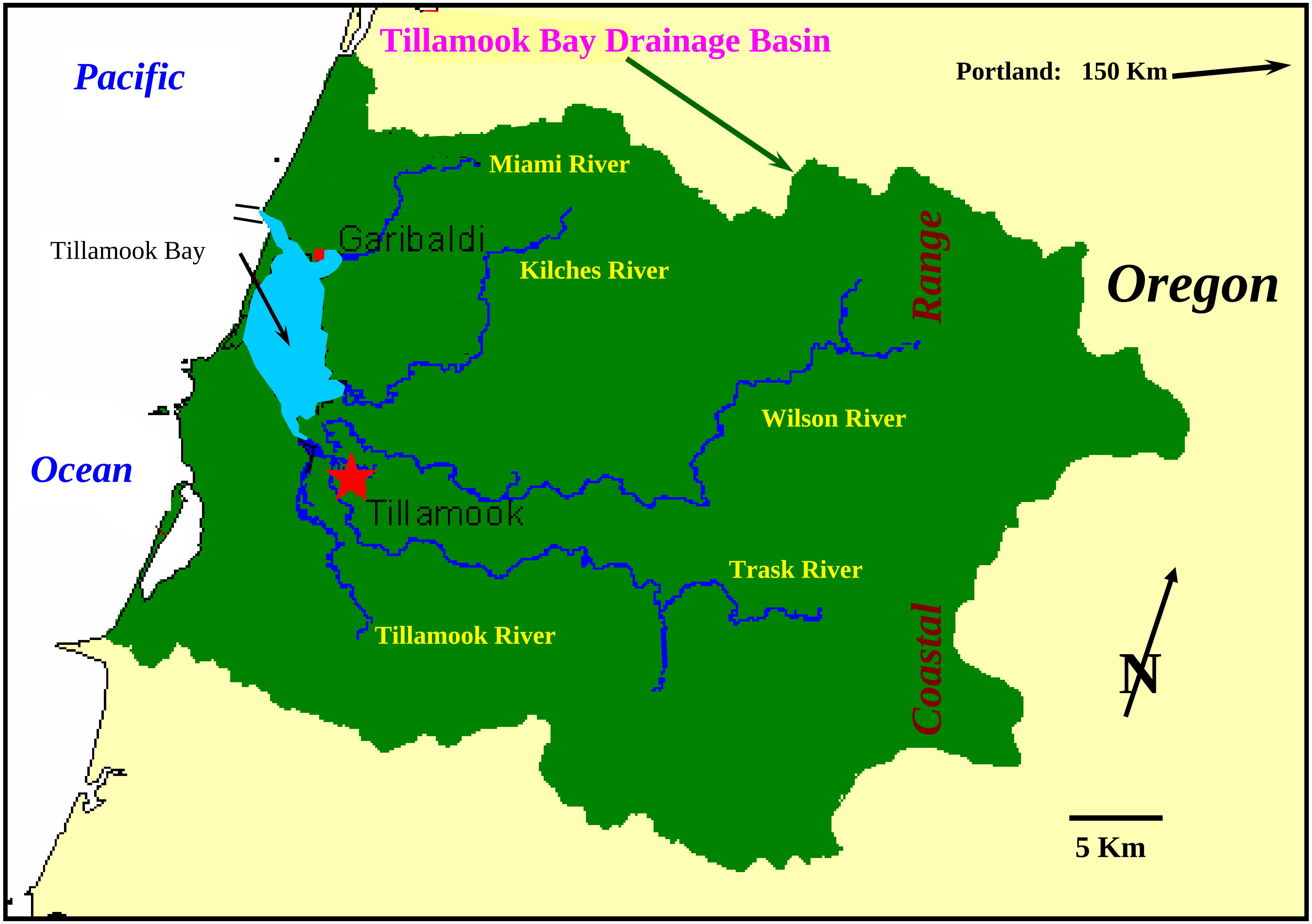


Figure 1. Site map for project area

Figure 2. TOP. Aerial view at north end of Tillamook Bay at extreme low tide, view is to the south. Note broad expanse of interconnected tidal flats and network of incised tidal channels. All tidal flats are submerged during high tide. BOTTOM. Aerial view at north end of Tillamook Bay showing jettied channel connecting the bay to the Pacific Ocean, view is to the northwest. Note constricted area of entrance near Kincheloe Point. Photo date is 4 June 2000 and tide was -2 ft MLLW, courtesy Port of Garibaldi

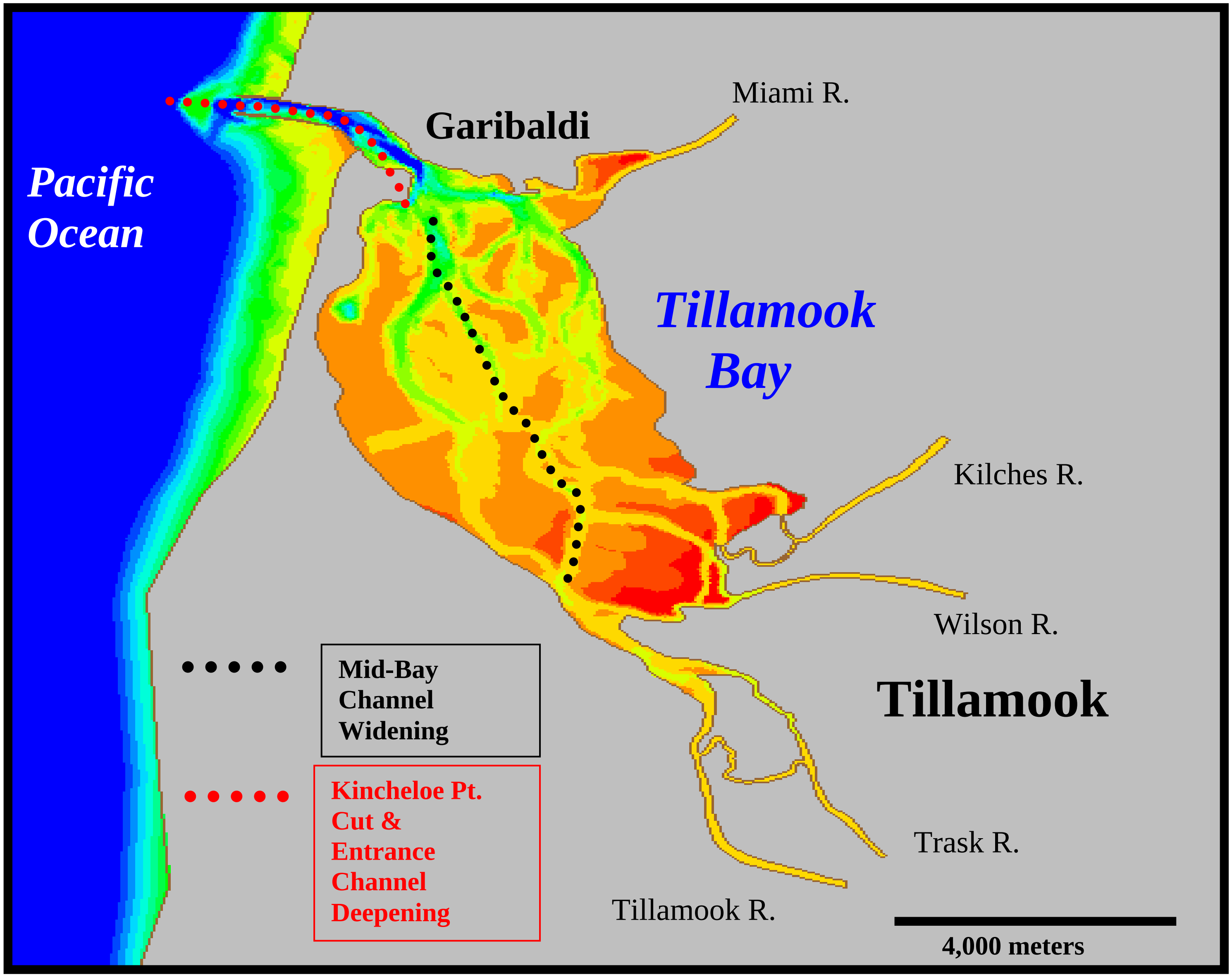
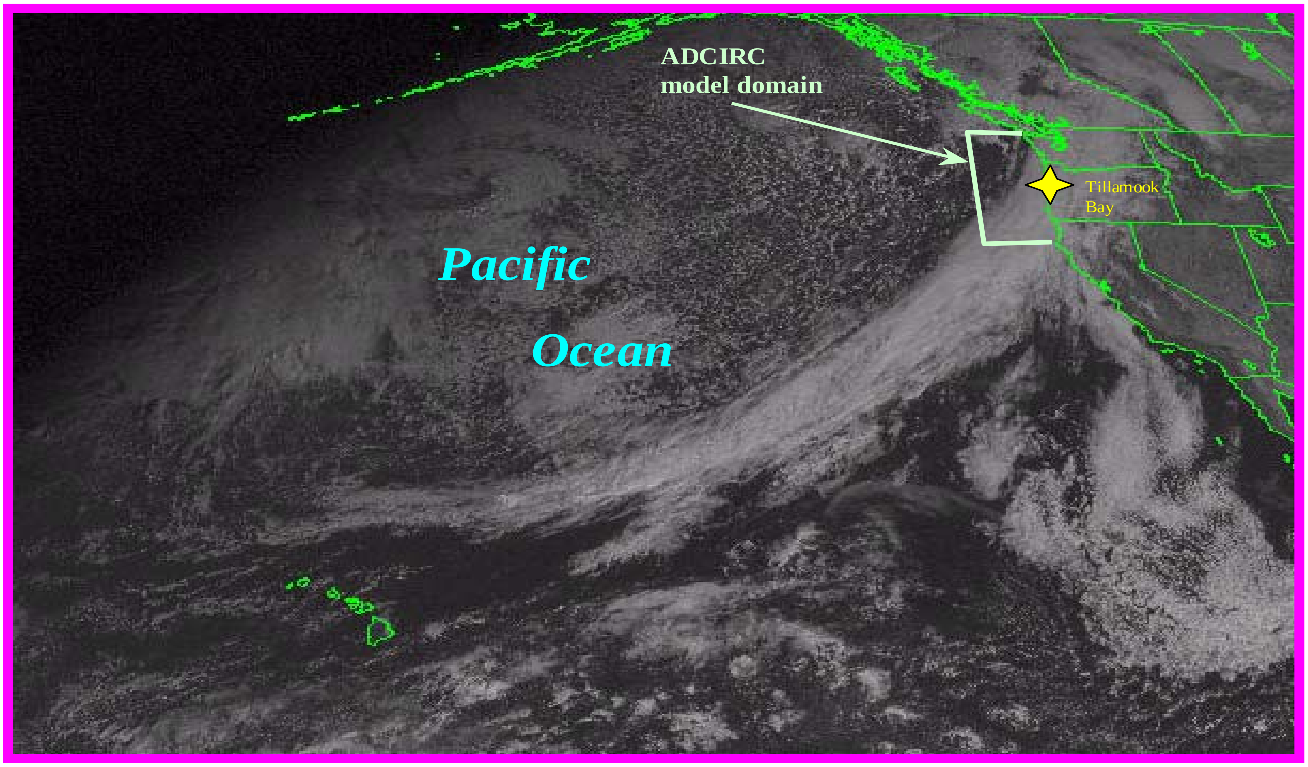


Figure 3. Present Tillamook Bay condition and alternative layout for plans A and B.



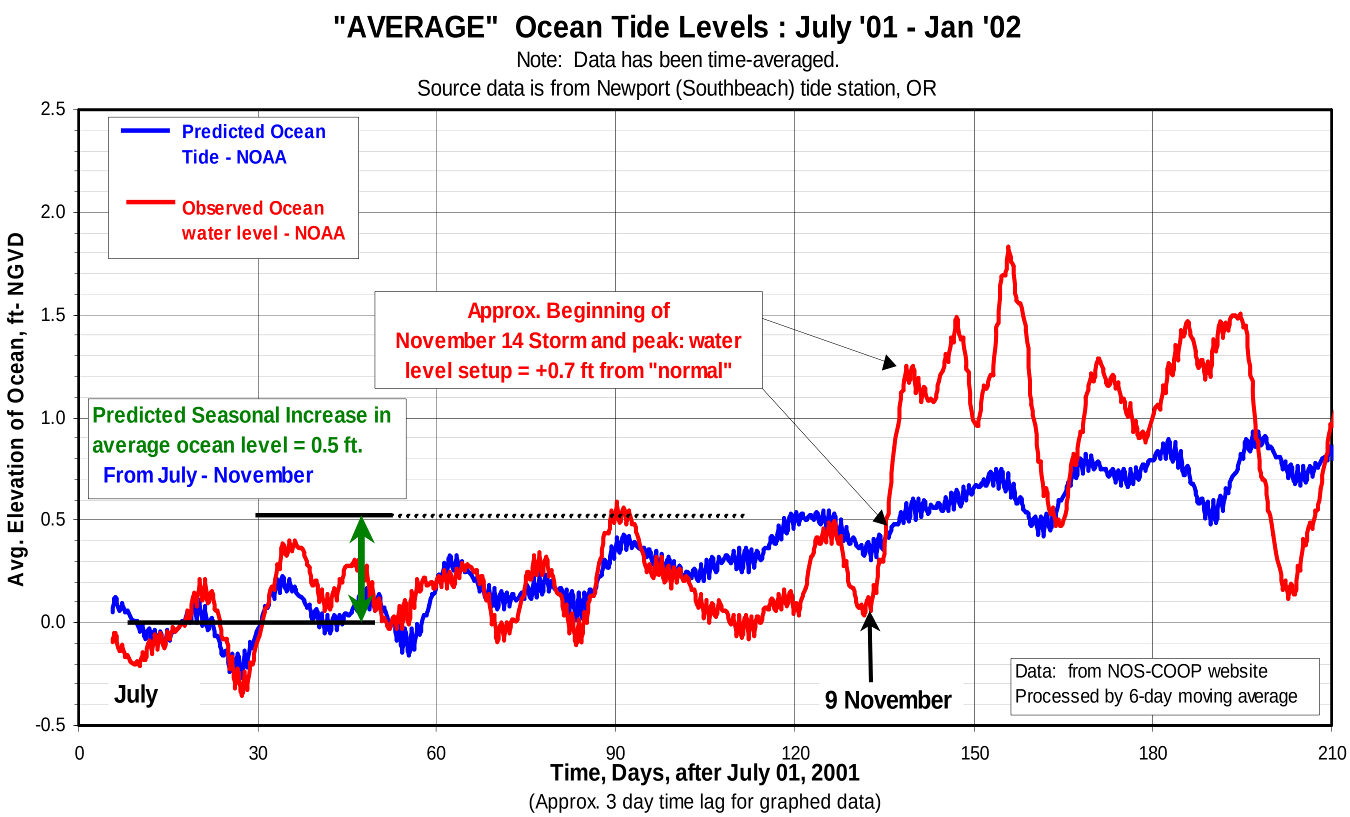
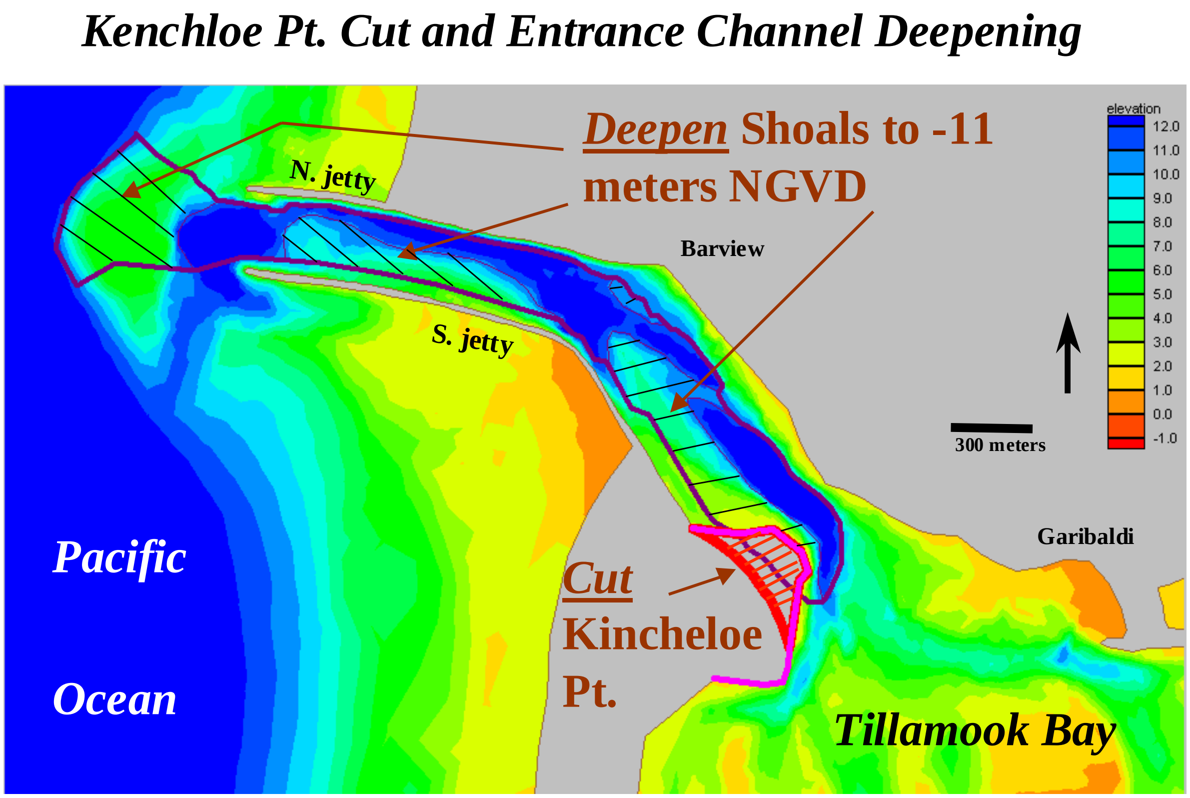


Figure 4. TOP. Satellite image of Northwest USA coast showing 14 November 2001 storm and ocean domain extent for Tillamook ADCIRC model. BOTTOM. Filtered tides for Tillamook Bay offshore showing season offset and transient set-up due to maritime storm. conditions



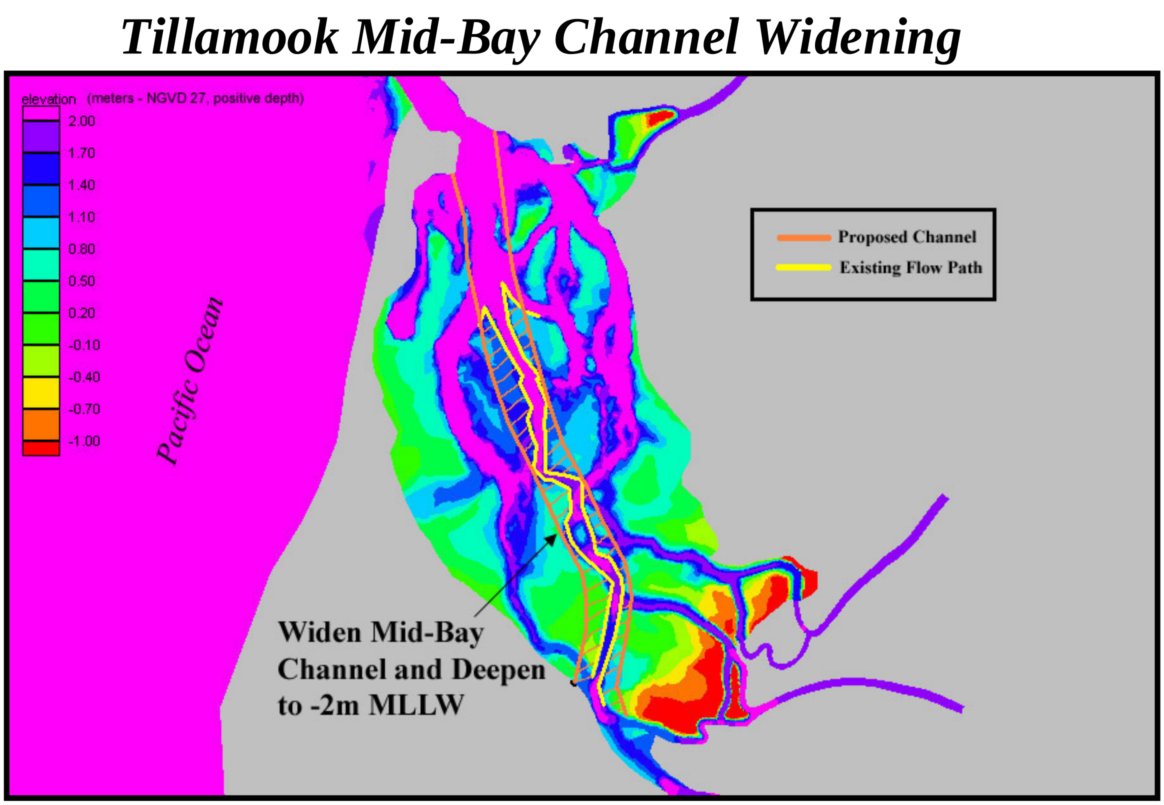
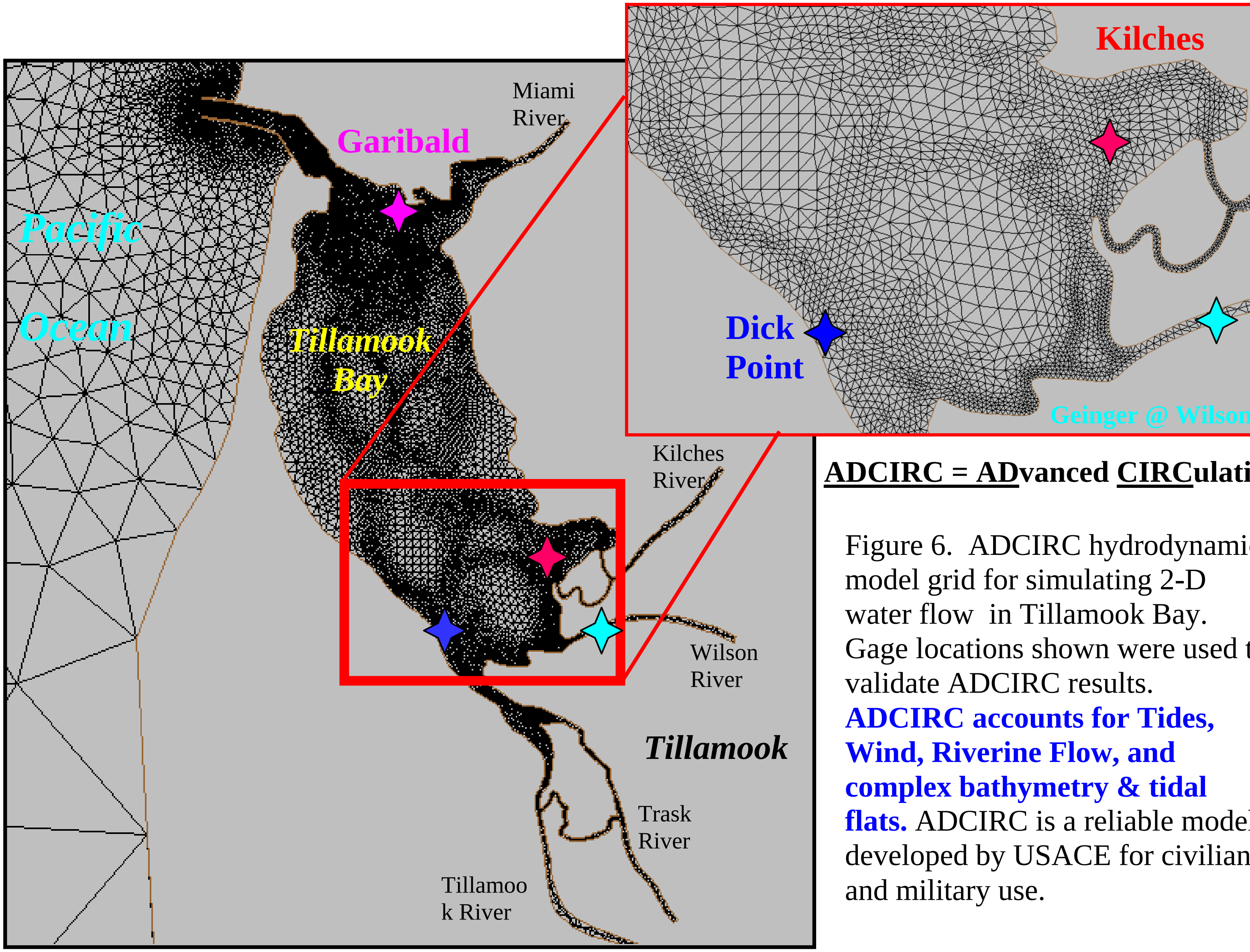
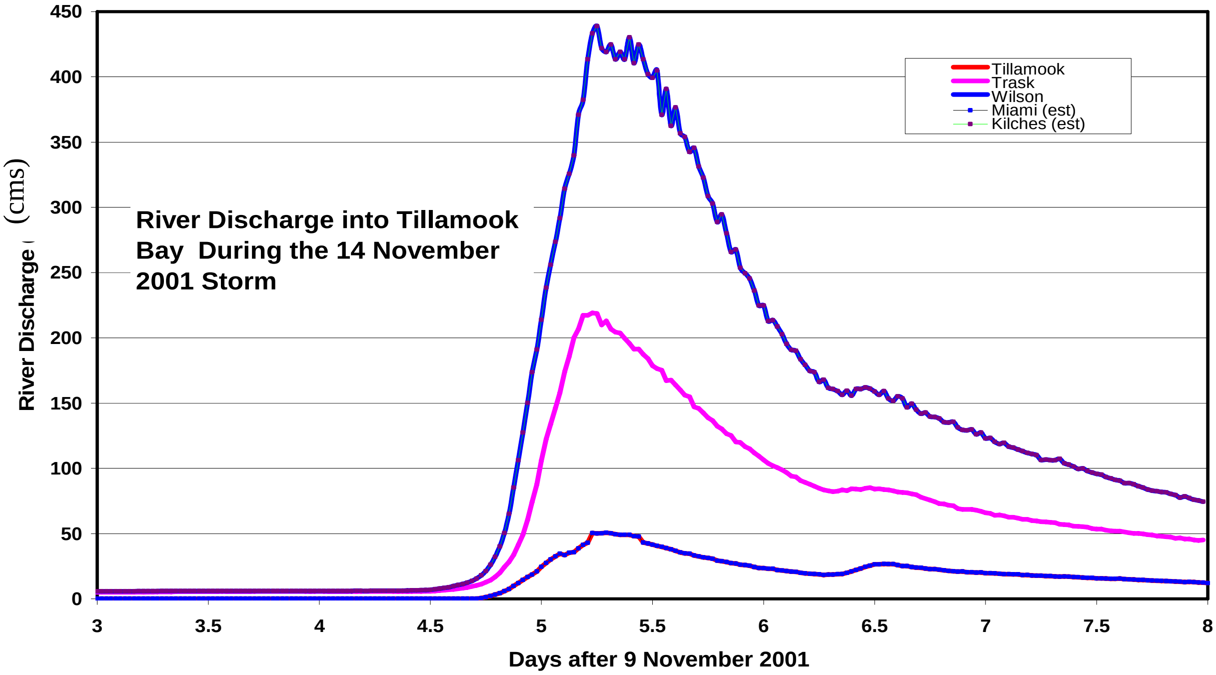


Figure 5. TOP. Alternative estuary modification plan A. BOTTOM. Alternative estuary modification plan B. Plan C is A + B



<u>ADCIRC = AD</u>vanced <u>CIRC</u>ulation

Figure 6. ADCIRC hydrodynamic model grid for simulating 2-D water flow in Tillamook Bay. Gage locations shown were used to validate ADCIRC results. **ADCIRC accounts for Tides, Wind, Riverine Flow, and complex bathymetry & tidal flats.** ADCIRC is a reliable model developed by USACE for civilian and military use.



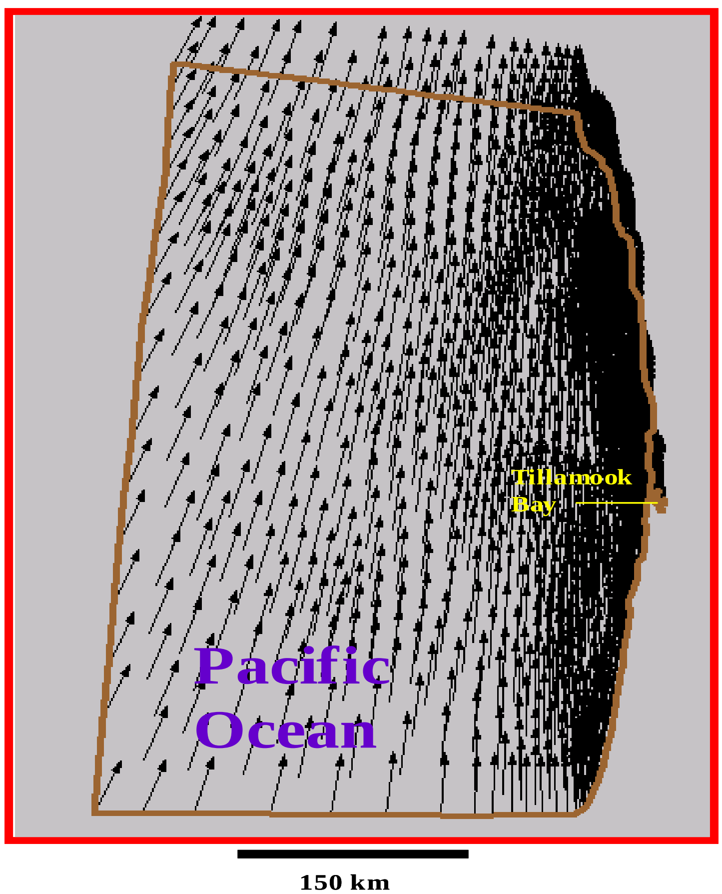
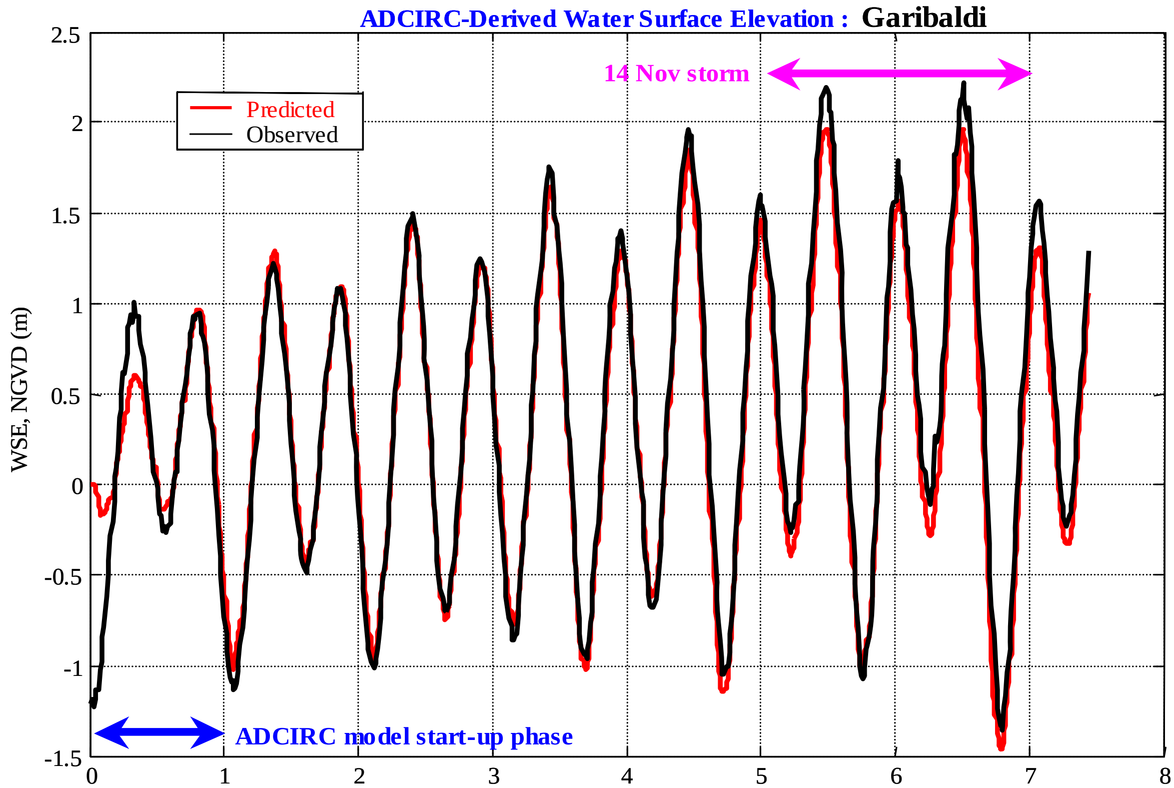


Figure 7. TOP. River flow hydrograph for 14 November 2001 storm.
BOTTOM. Windfield snapshot during passage of storm front over project area.



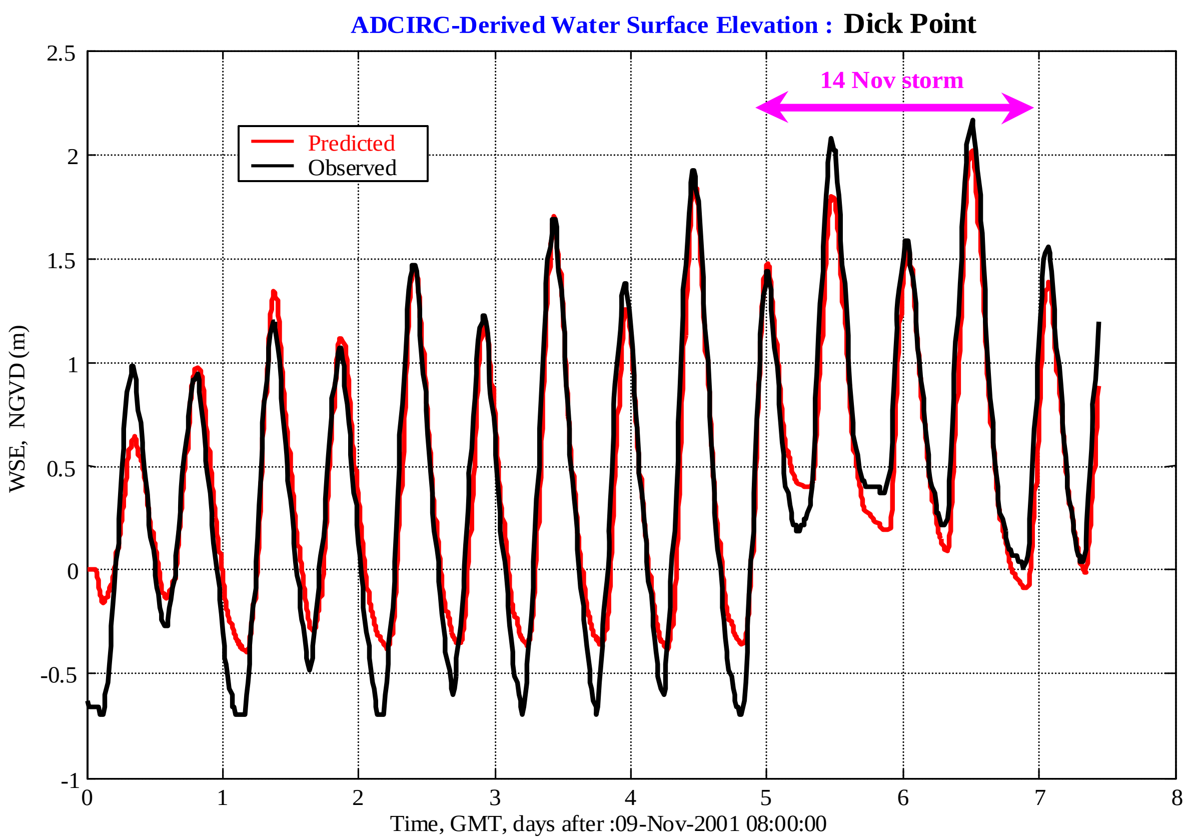


Figure 8. Validation results comparing observed WSE (stage) and ADCIRC model results

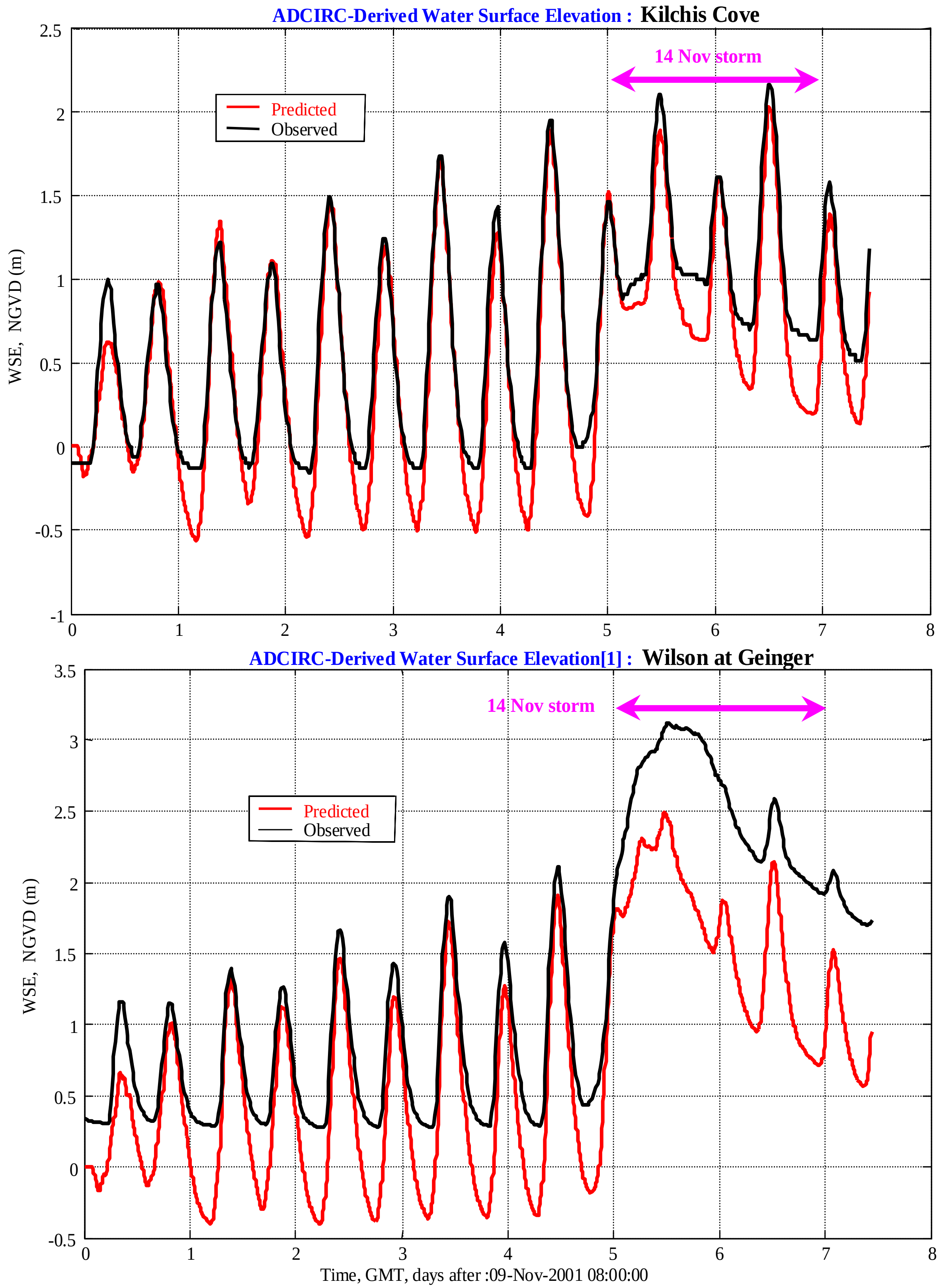


Figure 9. Validation results comparing observed WSE (stage) and ADCIRC model results.

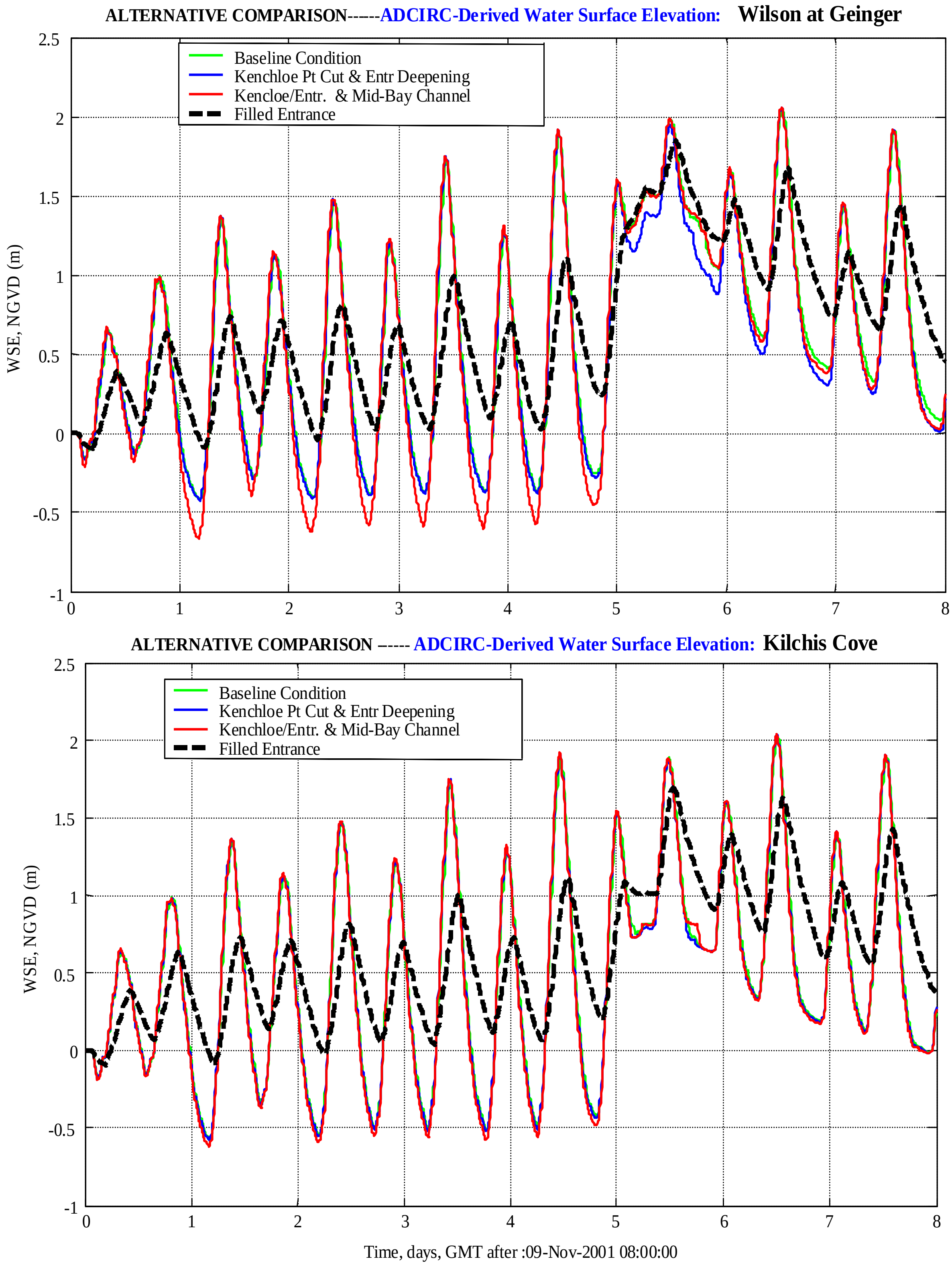


Figure 10. Alternative vs. existing condition results for WSE (stage) using the ADCIRC model.

NUMERICAL SIMULATION OF FLOW FIELDS IN THE TILLAMOOK BAY

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OREGON HEALTH AND SCIENCE UNIVERSITY

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1.0 Introduction

The Tillamook Bay is a shallow estuary with a large number of mudflats. The estuarine environment is fairly complex, and the US Army Corp of Engineers – Portland District (CENWP) is involved in a joint project with Tillamook County to study the environmental impacts on the estuary. As part of the project CENWP is studying flood damage due to storms and the impacts of mitigation solutions. The Center for Coastal and Land Margin Research (CCALMR) at the Oregon Health and Science University (OHSU) has been contracted to provide CENWP with a working model of the Tillamook Bay. The development of a working model involves the development of a computational grid, and calibration studies with ADCIRC, which is a depth – averaged finite element circulation model, and the computational engine to be used in the simulations. This report is a culmination of the combined efforts of CENWP and CCALMR. The calibration studies have been carried out using tidal gages, for both storm and tidal conditions. The 2001 bathymetric survey data from CENWP has been incorporated in the development of the numerical grid.

2.0 Data

The Tillamook Bay estuary is a shallow estuary with a large number of inter-tidal mudflats. The estuary receives riverine inputs from five rivers – Tillamook, Trask, Wilson, Kilchis and Miami (see Figure 1). The river discharge contributions from the individual rivers (for the last 6 years) are shown in Figure 2. Major contributions of river discharge into the Tillamook estuary are via the Trask, Wilson and Kilchis rivers. A number of narrow channels provide the pathways for both the riverine discharge out of the estuary and the tidal flows in and out of the estuary. The existence of the narrow channels, interspersed with broad shallow tidal flats, make numerical simulations a challenging effort.

The USACE maintains 5 tidal gages inside the estuary (see Figure 1). The Garibaldi gage is located close to the mouth of the channel and is directly influenced by the ocean conditions at the mouth of the estuary. The remaining 4 gages are located further upstream and show a stronger influence of river discharge in their elevation data. The data from these gages has been used to validate the numerical model results. A comparison of tidal elevation data at Geinger with the data at the different gages shows that the Geinger gage consistently has a higher mean elevation than the other gages (see Figure 3). We hypothesize that this is due to an incorrect vertical datum at Geinger. For comparison purposes in this report, the data at Geinger has been consistently down-shifted by 0.5 m, a correction that needs to be verified in the field. Both the river discharge and tidal data has been obtained from CENWP.

3.0 Numerical Model

The numerical model used in this study is a two-dimensional finite element model known as ADCIRC. As used, ADCIRC simulates the depth-averaged barotropic flow conditions. It is a finite amplitude non-linear model and can also simulate wetting and drying of tidal flats, which is a crucial element of modeling Tillamook Bay. The vertical datum in the model runs was Mean Sea Level (MSL), which is the same as the NGVD datum. The bathymetry data was transformed from Mean Low Low Water (MLLW) to NGVD by adding 1m. The offshore tidal boundary conditions are specified in the frequency domain. Nine tidal components (see Table 1) have been chosen to represent the main tidal constituents observed at this site. Non – linear tidal components are not specified in the offshore bathymetry and allowed to develop within the model as the tides propagate onshore. The tidal amplitudes and phases are determined from an ocean tidal model (Myers and Baptista, 2001). Tidal amplitudes and phases remain fixed in the model. The nodal correction factors on the other hand depend upon the start of run and are determined using Mike Foreman's tidal analysis package. A mean offset component $\mathbf{Z_0}$ is provided to account for any offset not accounted for in the tidal forcings. For the calibration runs this offset was set to 0. The boundary condition at the river end is specified as a time series of flux per unit width. Apart from that, the model can also account for wind effects, which is specified as a time series of surface stresses and atmospheric pressure over the whole domain. Bottom friction effects have been accounted for by using a non-linear quadratic drag formulation. A spatially varying drag coefficient is specified using the manning formulation.

$$c_f = \frac{n^2 g}{h^{\frac{1}{3}}}$$

where, c_f is the bottom drag coefficient, *n* is the manning coefficient, *h* is the local depth and *g* is the acceleration due to gravity. After sensitivity analysis, we chose n = 0.030, for our runs.

The model outputs water elevation and horizontal velocities (along the north – south and east – west direction). The output files can be saved in binary or ascii format. The required input and output files are

- **Input Files**
  - Fort.15 This is the master control file specifying the length of the run, time step, ramp – up function, wetting and drying parameters, offshore tidal boundary conditions, nodal factors, time step for wind forcing, time step for river forcing, output storage type etc.
  - Fort.14 Grid file with bathymetry information. (Vertical datum is NGVD).
  - Fort.21 Drag coefficients for bottom friction
  - Fort.20 River discharge per unit width at all the river boundary nodes. Length of file dependant on the number of river boundary nodes, length of simulation and river discharge time step specified in Fort.15
  - Fort.22 Wind induced drag coefficients and atmospheric pressure over all the nodes as a function of time. Length of file depends upon length

of simulation, number of nodes in the grid and the wind forcing time step in Fort.15

- **Output Files**
    - Fort.63 Surface elevation data as a function of space and time. Ouput can be in ascii or binary format (specified in Fort.15). Output time step is specified in Fort.15
    - Fort.64 Horizontal velocity data. Horizontal velocity is output in the east – west and north – south coordinate system.

4.0 Numerical Grid

The Tillamook Bay estuary consists of numerous tidal flats and narrow channels. The grid was designed to carefully represent all the channels of the estuary. To prevent inadvertent drying of the channels by the model, a minimum of two elements is required across the channel width (a larger number is preferred). At the same time, numerical stability considerations limit the smallest size that the elements can get while keeping the time step within computationally feasible limits. The grid development involved several iterations of model simulations and grid modifications. The results presented in this report have been run on four different grids. Grid 1 is a fairly detailed grid of the Tillamook Bay estuary and the offshore bathymetry (see Figure 4). Grid 2 is a modified form of Grid 1 in which the offshore grid has been extended in the north and south directions. This was done to determine the effects of wind blowing over larger offshore domains on the dynamics within the estuary. Grid 3 is a further modified version of Grid 2, in which the river boundaries have been cut-off fairly close to the estuary. The final grid, Grid 4, was developed from Grid 1 by CENWP. It covers the same extent as Grid 1 did, except that in Grid 4 the river boundaries have been cut short and changed to allow easier passage of discharge into the estuary. Anomalous depths and badly shaped elements inside the estuary have also been removed after careful examination.

5.0 Model Simulations

Model simulations have been divided into two periods. In the first case we chose a time period with very low river discharge so that the main forcing was tidal. The aim was to test how well the tidal oscillations are simulated by the numerical model. In the second case we chose the time period centered around a storm event which was accompanied by strong wind conditions and higher levels of river discharge into the estuary.

5.1 Tidal flows test case

The tidal flow test case was run for a 15-day simulation extending from 04/14/2001 to 04/29/2001. The run had a 5-day ramp-up period, which is included in the 15-day simulation period. The river discharge during this period was very low (see Figure 6) and thus the river boundaries were treated as closed boundaries for this test case. No winds were forced for this run. Tides were forced from the output of a regional tidal model in the frequency domain, all along the offshore open boundary. The aim of this test was to observe how well the model propagates tides into the estuary. The model simulations were found to be stable for time steps no greater than 2 seconds. This limitation is due to the numerical restrictions placed on the model by the smallest elements in the grid. Simulations with time step greater than 2 seconds blew up due to numerical instabilities. Thus, a time step of 2 seconds has been used for all the calibration runs. It might be possible to run the model with a time step of 3 seconds if the resulting flow field is not very strong.

Figure 7 shows the model-to-data comparisons of a tidal run in which a large horizontal diffusion value of 10 m^2s^{-1} was used. This was done to remove noise due to boundary effects in the northern ocean boundary, and also to stabilize the solution at the mouth of the estuary. However, numerical instabilities continued to grow inside the estuary. These instabilities were linked to the horizontal diffusion and increased with increase in horizontal diffusion. The numerical solutions were found to be unstable for values of horizontal diffusion greater than 1 m^2s^{-1}. This is contrary to what we would expect, where the horizontal diffusion is expected to decrease noise. We hypothesized that inside the narrow channels of the estuary, the horizontal diffusion was having a negative impact by spreading the noise in the flow field into the much shallower tidal flat region, where the noise was amplified instead of being suppressed. Figure 8 shows the model data comparisons for a test case in which a spatially varying horizontal diffusion coefficient is used. For this simulation the horizontal diffusion coefficient was 3 m^2s^{-1} in the region around the mouth of the estuary, 50 m^2s^{-1} around the northern offshore boundary and 1 m^2s^{-1} everywhere else. The results are much better when compared to those in Figure 7. From personal communications with Michael Knutson at CENWP, it was found that the tidal gages at Kilchis and Geinger come out of the water during low tides. This would explain the cutoff in the tidal signals of these gages during low tides. There seems to be a phase lag between model and data results at Garibaldi. Since this phase lag was not observed at any of the other stations and tends to be constant, it is probably due to a clocking error in the signal. Both these simulations were conducted on Grid 1. Simulation results conducted with Grid 4 are shown in Figure 9. With Grid 4, the results at Dick-Point are much better. This is because in Grid 1, one of the channels feeding into Dick-Point was inadvertently drying. That problem was fixed with the modified grid of Grid 4. The simulations with Grid 4 also lead to stronger tidal signals at the upstream gages of Kilchis, Geinger and Carnahan. Due to the drying of the Geinger and Kilchis gages, it is not possible to determine how much off the model results are from the data during low tides. In conclusion, the model does reasonably well in simulating tidal flow conditions. The horizontal diffusion coefficient inside the estuary should not be allowed to be greater than 1 m^2s^{-1}, as that leads to the growth in numerical instabilities. To maintain channel connectivity it is important to have at least 3 elements across the channel if not more.

5.2 Storm Event

A storm front passed through the Tillamook Bay area around 11/14/2001. Accurate modeling of such storm events would prove extremely useful as it would provide engineers with regions of flooding. Sensitivity studies involving the effects of bathymetric changes on flooding patterns during storm events can also be attempted. With this goal in mind, we concentrated our efforts in trying to simulate the November 14th storm with the ADCIRC model.

Wind data obtained from a NOAA offshore buoy (Yaquina Bay buoy) showed strong offshore winds blowing in from the south during this time period (see Figure 10). Due to Coriolis forcing, the direct effect of strong winds blowing in from the south will be a setup at the mouth of the estuary. Since the numerical model requires a large ocean surface area to develop the required Coriolis effect, we carried out the simulations over larger grids (see Figure 5 for a comparison of the extents of coverage between the smaller and larger grids). The major problem with using the Yaquina Bay buoy data to represent winds is that it does not provide us with any spatial variations of the wind. Alternatively, we have used atmospheric forecast models to provide us with required wind forcing. The wind data was obtained from two numerical weather prediction models. The first is the Medium Range Forecast (MRF) produced by a Global Spectral Model (GSM) at the National Center for Environmental Prediction (NCEP). The MRF provides data on a relatively coarse grid at a low temporal frequency. Higher spatial and temporal resolution data is provided by a local forecast run of the Advanced Regional Prediction System (ARPS) at Oregon State University (OSU). A weighted average of these two sources is used to obtain the desired wind conditions, with the OSU data (when/where it exists) given a weighting twice that of the MRF data. Though this is not real data, it does provide us with both spatial and temporal wind information. The comparison between the forecast wind and buoy wind data is given in Figure 11. The observed river discharge also increased quite considerably during the storm event (see Figure 12), with the discharge at Wilson river increasing from almost 0 to over 400 cms in one day. The effect of both the wind setup and river discharge can be observed in the gage data (see Figure 13). The gage at Garibaldi was the only gage that was working consistently over this entire period. All the other gages stopped working during the storm. Once again the Geinger gage is showing a mean level much higher than any of the other gages, and just like in the tidal test case, we reduce the vertical datum by 0.5 m for comparison with model results. The Dick-Point gage is also showing a higher mean level, specially during the period before the storm when the discharge levels are low and the winds are not very strong. This might also be related to the vertical datum of the gage being shifted, but we do not know that for sure. As a result we did not try to adjust the datum of this gage.

For model simulations we now force the tides at the offshore boundaries, wind over the entire domain and river discharge per unit width at all the river open boundaries. Since river discharge data is available only for three rivers (Figure 12) we assume that the discharge at Miami river is the same as the discharge at Tillamook river and the discharge at Kilchis river is the same as the discharge at Wilson river. The basis for this assumption is the 5-year river discharge data in Figure 2, which shows some level of compatibility between Miami and Tillamook river and Wilson and Kilchis river respectively. Wind effects are accounted for by providing time series of surface stress over the entire domain. Surface stress is related to wind speed and direction by

$$\left(\tau_{Wx}, \tau_{Wy}\right) = \rho_a C_{Ds} \left|\vec{W}\right| \left(W_x, W_y\right)$$

where ρ_a is the air density [kgm^{-3}], C_{Ds} is the wind drag coefficient and $\vec{W}(x, y, t)$ is the wind velocity at 10m above the sea surface, with manitude $|W|$ and components W_x and W_y [ms^{-1}] . The drag coefficient C_{Ds} is parametrized such that the transfer of momentum from air to ocean increases with wind speed.

$$C_{Ds} = 10^{-3}\left(A_{W1} + A_{W2}\left|\vec{W}\right|\right)$$

where A_{W1} and A_{W2} are 0.75 and 0.067 respectively. These coefficients have been calibrated in literature for strong wind conditions (Garratt, 1977).

Numerical simulation results for the storm event are shown in Figure 14. The simulation was done on Grid 1. The net effects of wind setup and river discharge can be seen in Figure 15, where the tidal signature has been averaged out using a running average window with a window length of one day. The tidal signal at the Dick-Point gage is more damped in the model results when compared to the data and the observed wind setup is much higher than the simulated wind setup at the Garibaldi gage. Since this wind setup could be related to offshore wind forcing and subsequent turning of water mass towards the coast due to coriolis effects, one of the causes of the model performing poorly could be that the ocean part of the grid is too small to adequately generate enough transfer of water mass towards the coast. With this in mind the model was rerun with Grid 2, which extends over a larger domain in the ocean (see Figure 5 for a comparison of Grid 1 and Grid 2). The results of that simulation are given in Figure 16 and Figure 17. The model has some difficulty with the northern boundary of the grid and blows up after 12 days of simulation (see Figure 18). The setup in the model results at Garibaldi, though much more significant than before are still not adequate. This maybe because of local wind effects, which would amplify the setup at Garibaldi due to the north-south orientation of the estuary (see Figure 1). The wind information available to us is from a numerical model that is run on a much larger scale, and does not account for local winds. Another possibility is that the formulation used to wind speeds and direction to surface stresses is inadequate. This however is unlikely because these formulations have been used exhaustively in the literature. Apart from the setup issue, the tidal signature at Geinger shows a poor comparison between model and data results. This is probably due to the way the river bed was handled in the grid. In reality, the river bed slopes above the mean sea level a short distance upstream of the estuary. To allow transport of river flux from the river boundaries into the estuary without causing drying due to numerical instabilities, the upward slope of the river beds was removed from the grid. This probably led to a deeper penetration of the tides in the model. To prevent this the model was run on a different grid (Grid 3), which differed from Grid 2 in that the rivers were cut-off before the river beds sloped above the mean sea level, hence removing any need to change the bathymetry. The results of that run are shown in Figure 19 and Figure 20. The tidal signature is much better represented at Geinger in this simulation. In all of these simulations, the Kilchis river dries up during the strong discharge period due to the propagation of numerical noise (see Figure 21). This might be because we are forcing too strong a discharge into the rivers (note that we assumed the discharge in Kilchis river being the same as the discharge in the Wilson river). Based on the success that we had with using the USACE modified grid (Grid 4) in the tidal test cases (see Figure 9), we ran a simulation for the storm event on the particular grid. The results are shown in Figure 22 and Figure 23. It is best to compare these results with those of Grid 1, given in Figure 14 and Figure 15, since both grids cover a similar extent of region in the ocean. Wind setup at Garibaldi is better represented in Grid 4. This is very encouraging because the model performance should improve if we extend the ocean domain of Grid 4, as we did for Grid 1. The Kilchis river however continues to dry due to numerical instabilities and this is an area of concern as it effectively removes the estuarine effects of strong discharge in the Kilchis river.

6.0 Conclusions

The aim of this project has been to get the ADCIRC model to simulate flows in the Tillamook Bay estuary with reasonable level of accuracy. The study was divided into two parts. In the first part we concentrated on the abilities of the model to propagate tidal flow. To simulate tidal flow, 9 tidal components were forced at the offshore boundary. The tidal amplitudes and phases were determined from a regional tidal model. The tidal simulations were carried out in a period with low river discharge so as to minimize effects from other forcings (such as river discharge) on the gage data. Simulations were found to be highly sensitive to horizontal mixing coefficients, and a spatially varying diffusion coefficient was applied to simulate the flows. Comparisons with data have shown that with appropriate horizontal diffusion coefficients and grid, the model can simulate tidal flows reasonably well.

The second part of the study involved simulating a storm event. This was a more complex case, as the estuary was forced by tides, winds and river discharge. Atmospheric numerical models were used to determine the appropriate wind forcing conditions, while the river discharge was forced by measured data. Since actual discharge data was not available for all the rivers, some approximations had to be made for discharge conditions. Simulation results showed that setup near the mouth of the estuary depends on the offshore extent of the grid. The setup is higher for grids that cover a larger area over the ocean. The wind setup was however still insufficient. This could in principle be because we need a larger grid over the ocean, or the drag coefficients that convert wind speed to surface drag need to be larger. More likely, however, the model to data disparity could be due to local wind effects that are not captured by the atmospheric models that were used to determine the wind forcings. Another area of concern in the storm simulations has been the drying of the Kilchis river during periods of strong discharge. This drying is an artifact of numerical instability and needs to be addressed if the effects of Kilchis river are to be investigated.

Acknowledgements

The authors would like to thank Michael Knutson, Hans Moritz and Jessica Hays of the United States Army Corps of Engineers (USACE) for providing us with the data used in this study. Hans Moritz and Jessica Hays also developed one of the grids (Grid 4) used in this study. Dr. Mike Zulauf of the Center for Coastal and Land Margin Research (CCALMR) provided us with the required wind forcings for the storm condition simulations.

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Table 1: Tidal Components forced at the offshore boundary in ADCIRC

Tidal Components	Frequency (rad/sec)
Z_0	0.0000000000
M_2	0.0001405189
S_2	0.0001454441
N_2	0.0001378797
K_2	0.0001458423
K_1	0.0000729212
P_1	0.0000725106
O_1	0.0000675977
Q_1	0.0000649546

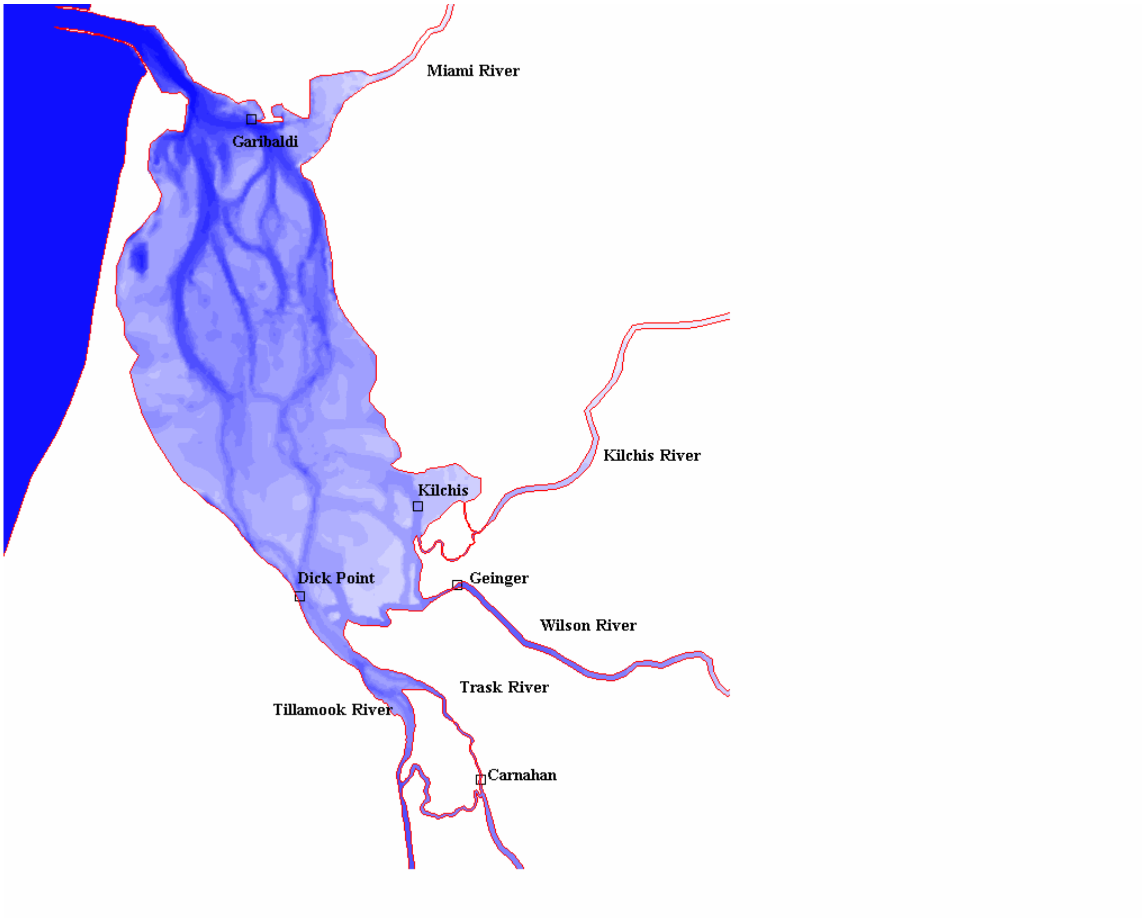

Figure 1: Tillamook Bay Estuary (Gage Locations marked by rectangles)

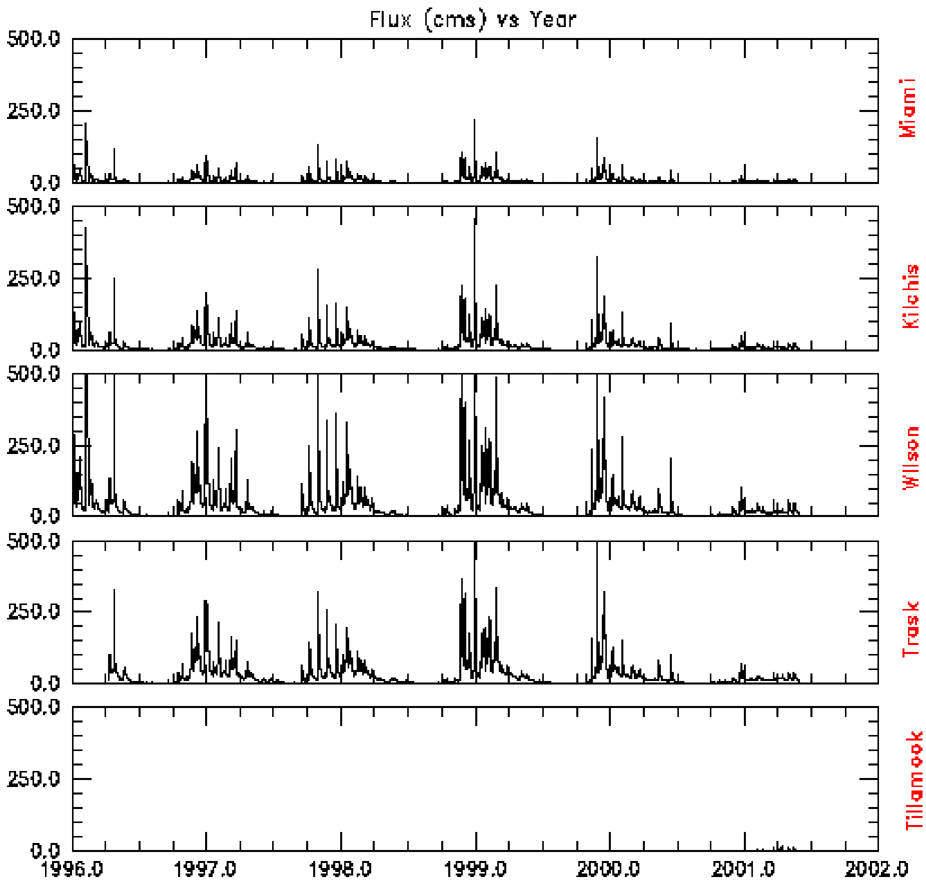

Figure 2: River discharge contributions from the 5 rivers into the Tillamook Estuary between 1996 and 2002.

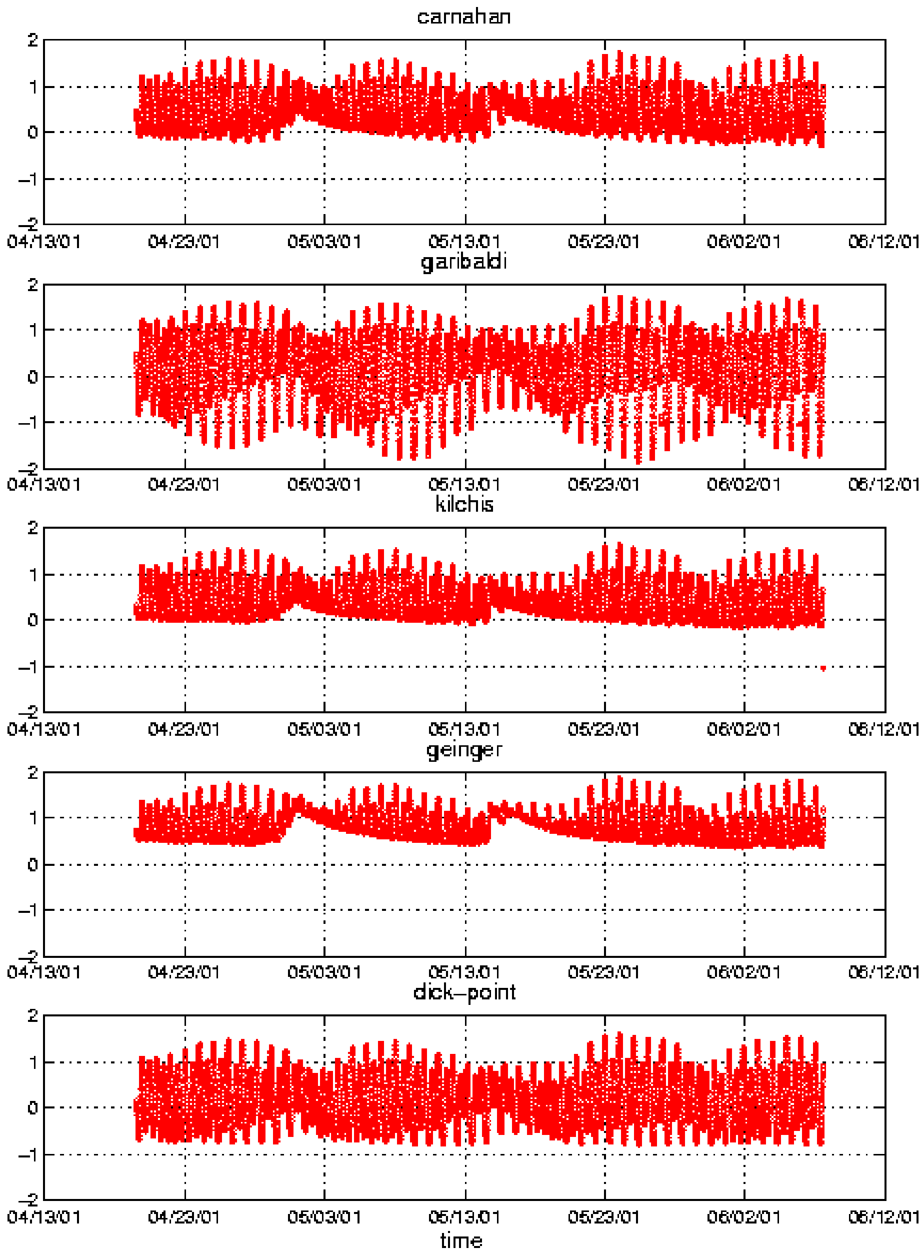

Figure 3: USACE gage data for a two month period

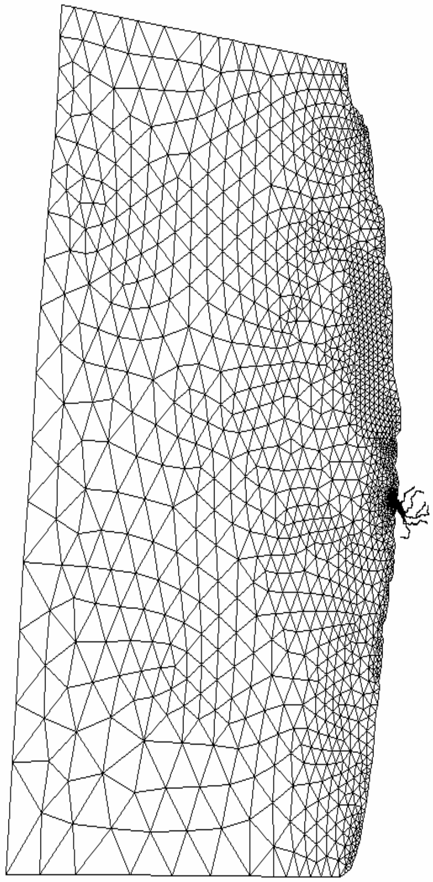

Figure 4: Tillamook Bay estuary GRID1

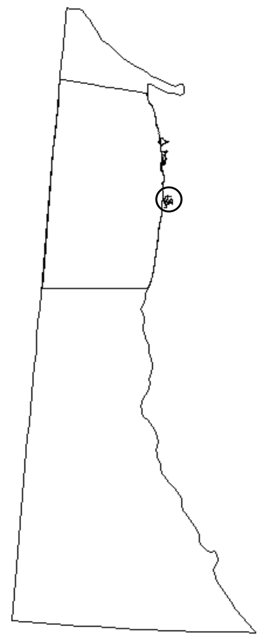

Figure 5: A comparison of offshore extent covered by the smaller grids (Grid 1 and Grid 4), and the larger grids (Grid 2 and Grid 3). Tillamook Bay estuary is circled in the image.

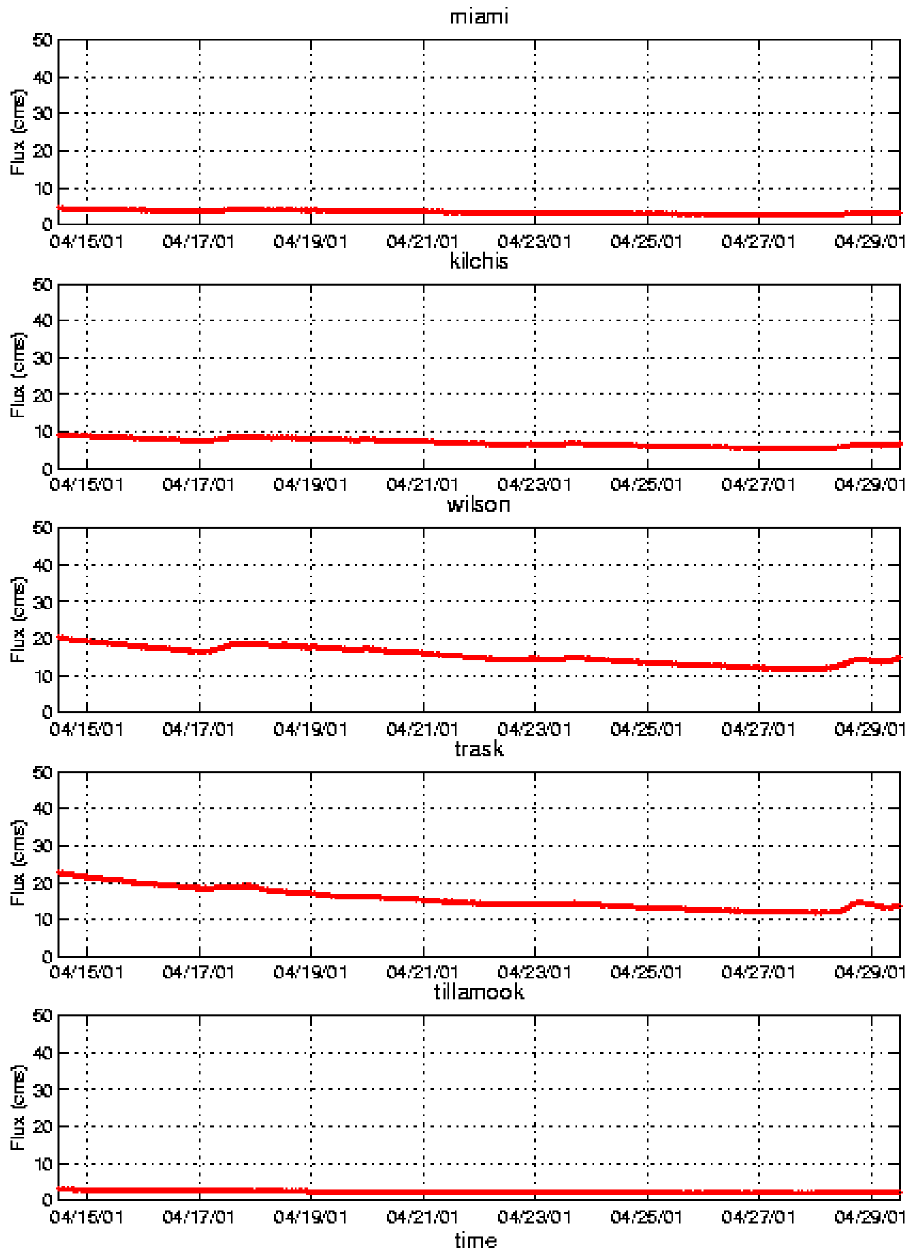

Figure 6: River discharge in cms for the time period of the tidal test case

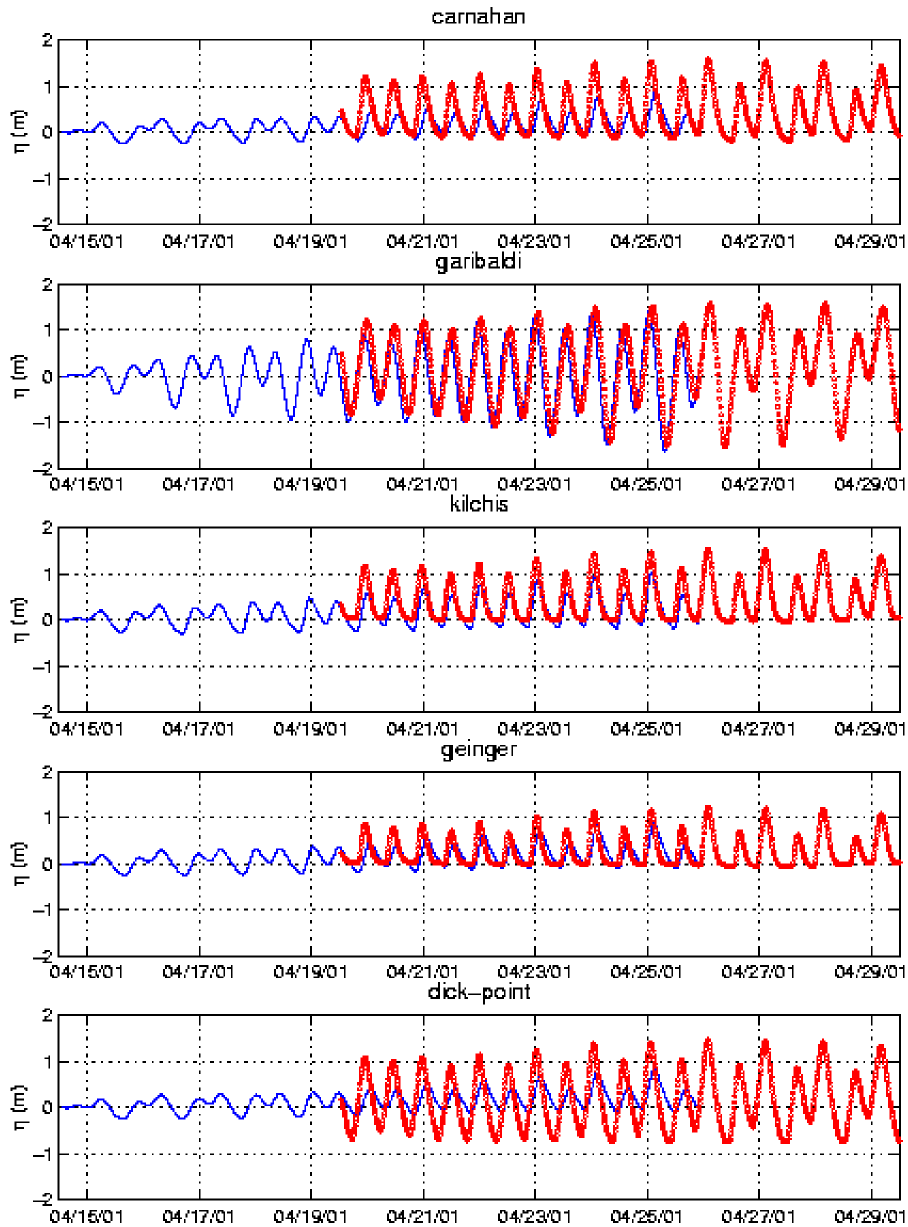

Figure 7: Model (Blue) to Data (Red) comparison of elevation (Tidal test case, constant horizontal diffusion, Grid1)

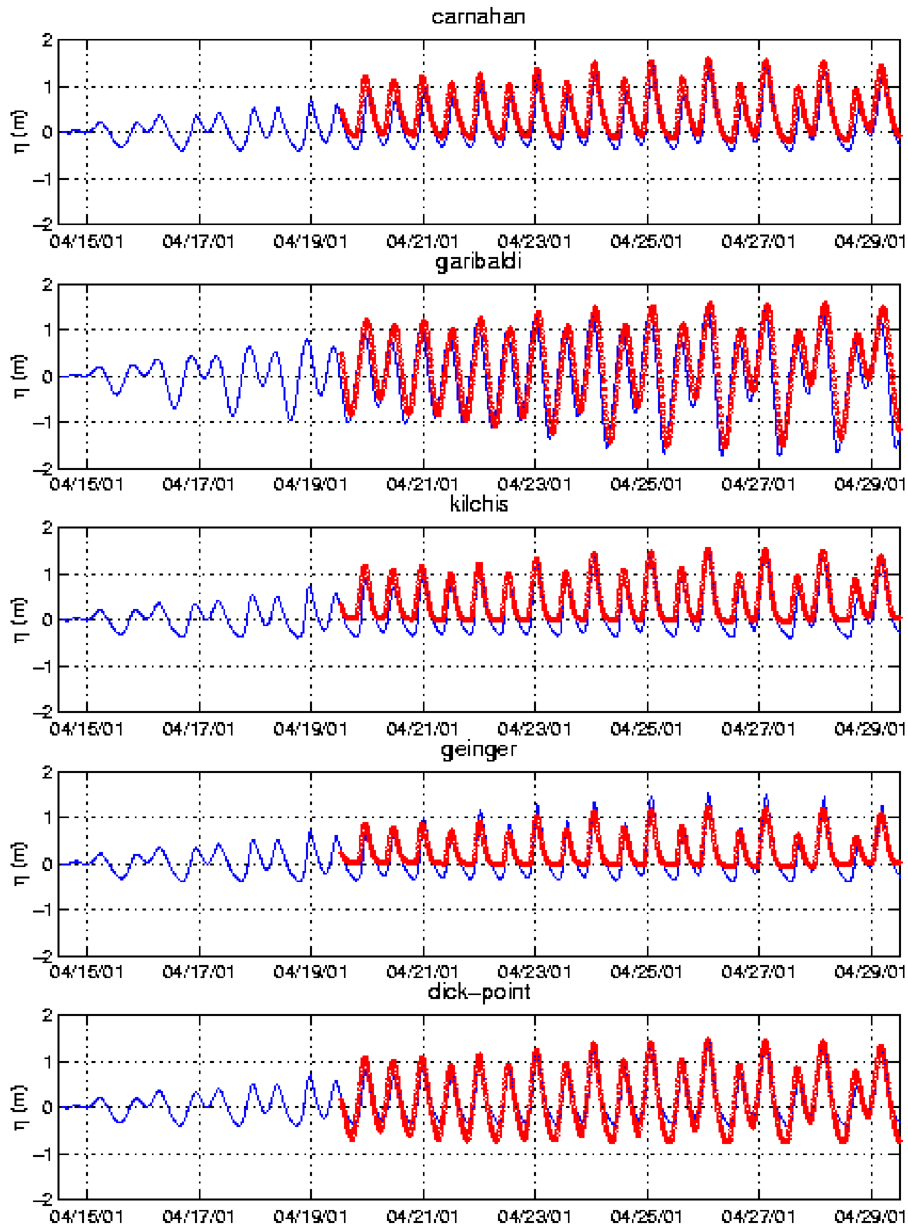

Figure 8: Model (Blue) to Data (Red) comparison of elevation (Tidal test case, spatially varying horizontal diffusion, Grid1)

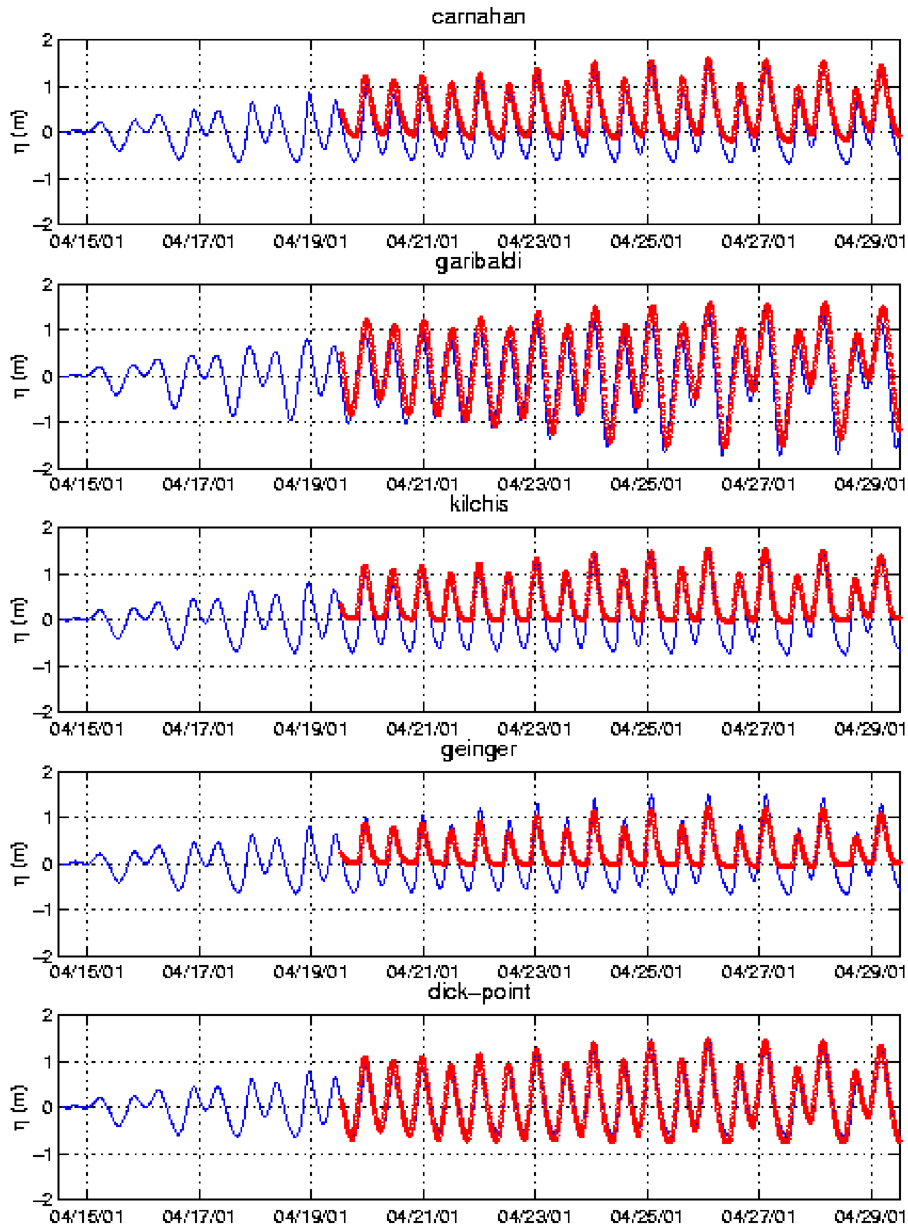

Figure 9: Model (Blue) to Data (Red) comparison of elevation (Tidal test case, spatially varying horizontal diffusion, Grid4)

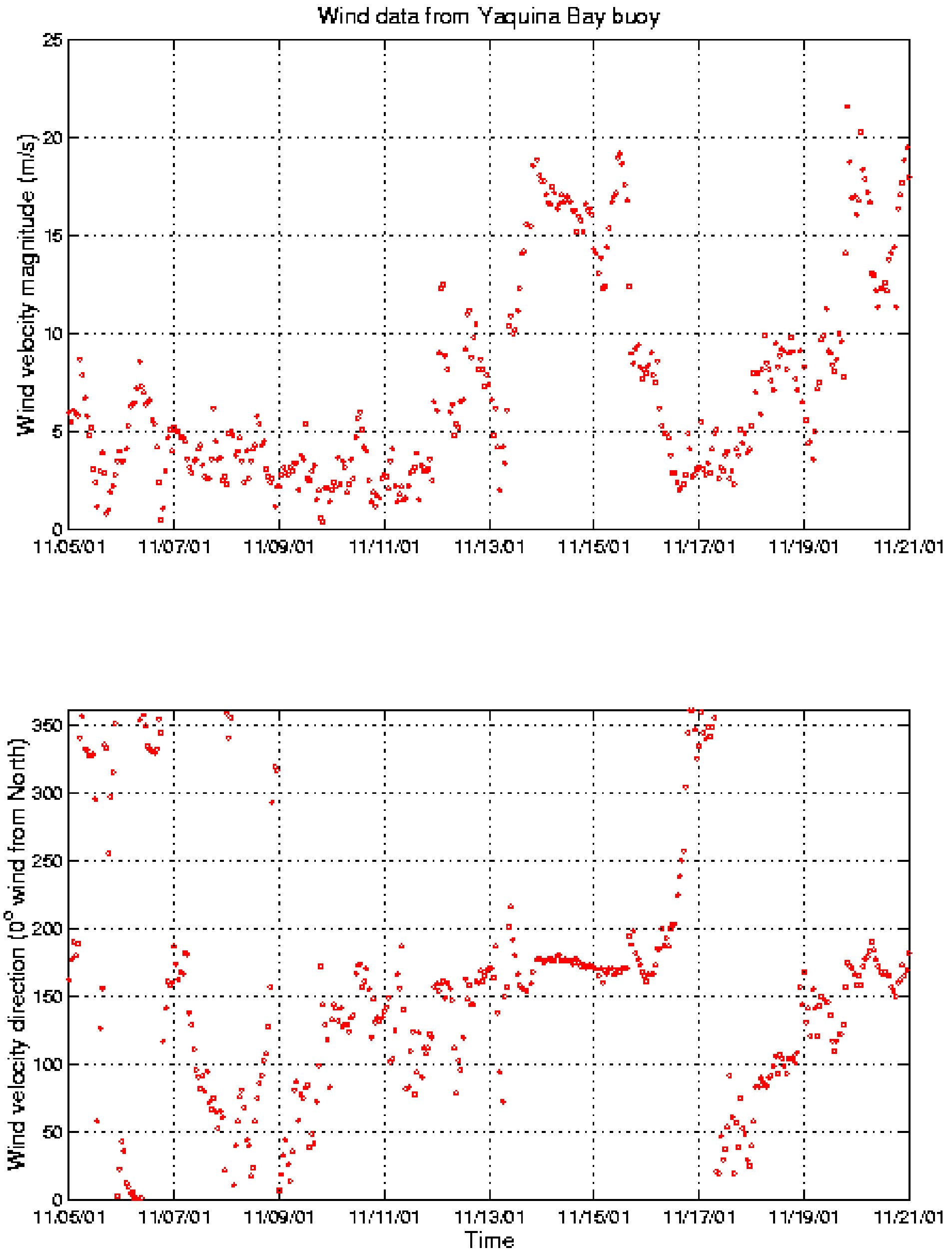

Figure 10: Offshore wind data from Yaquina Bay buoy. The buoy is approximately 67km due west and 118 km due south of the mouth of the Tillamook Bay estuary.

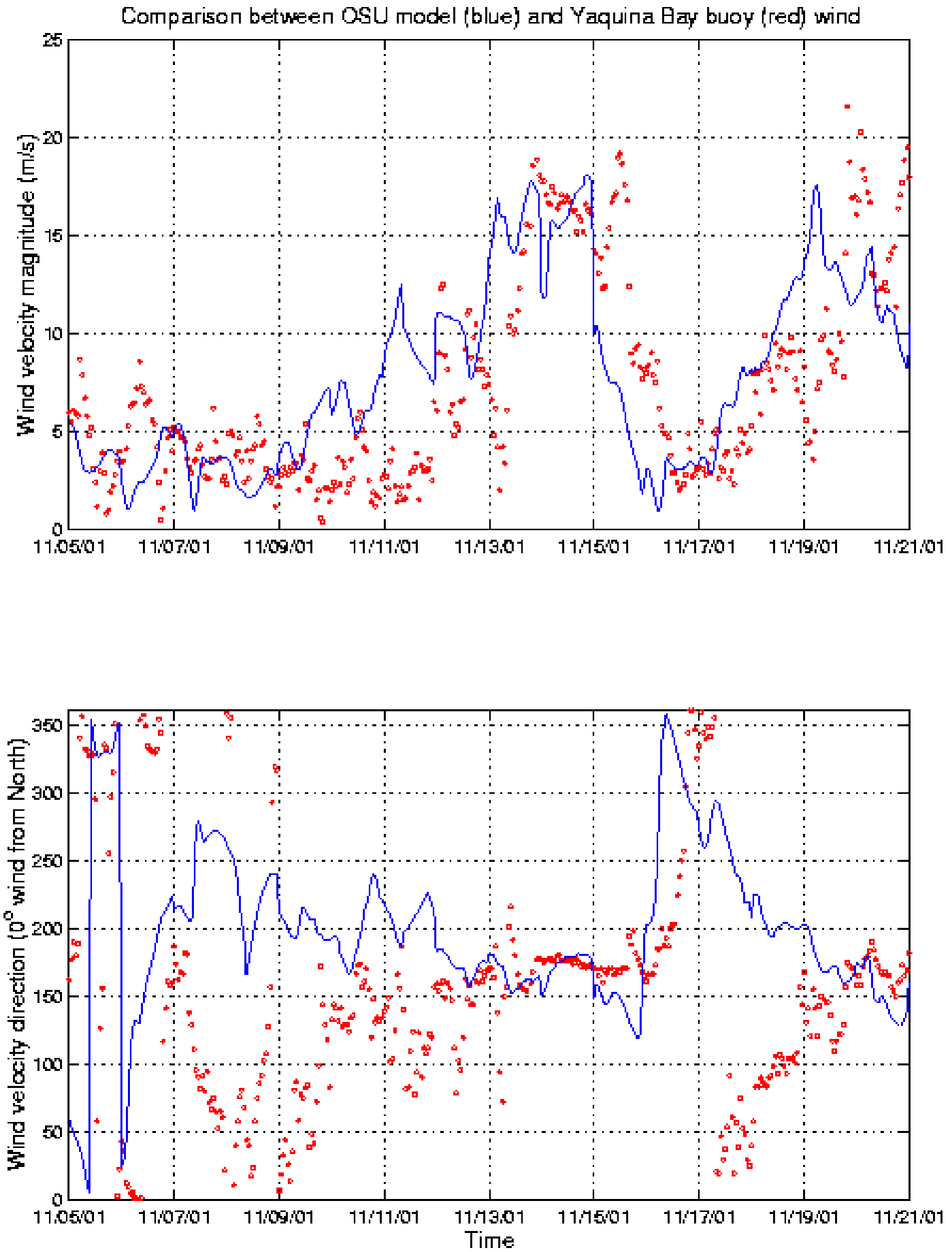

Figure 11: Comparison between OSU atmospheric model wind forecasts and Yaquina Bay buoy wind data.

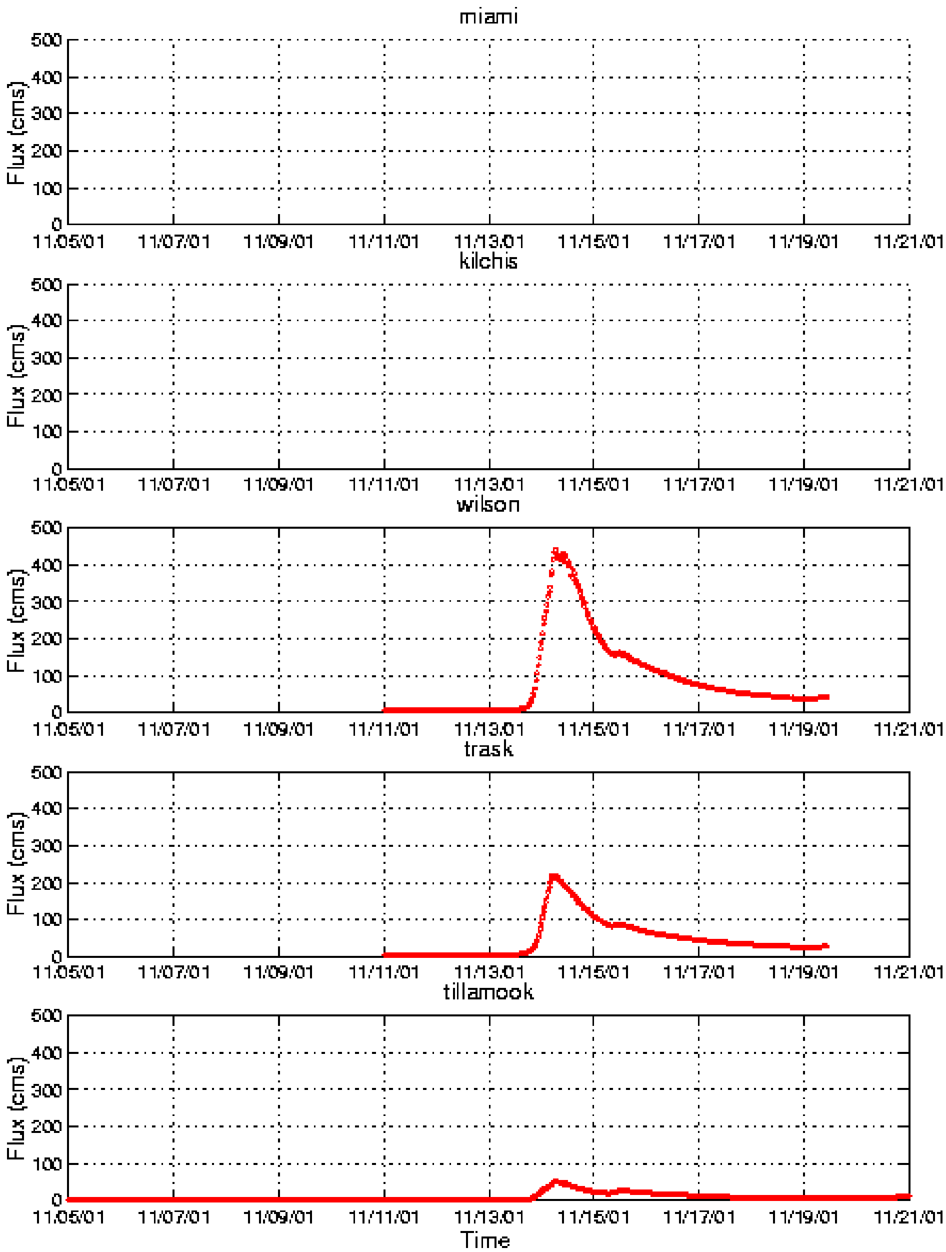

Figure 12: River discharge around the November 14th storm event. No discharge data was available for Miami and Kilchis rivers.

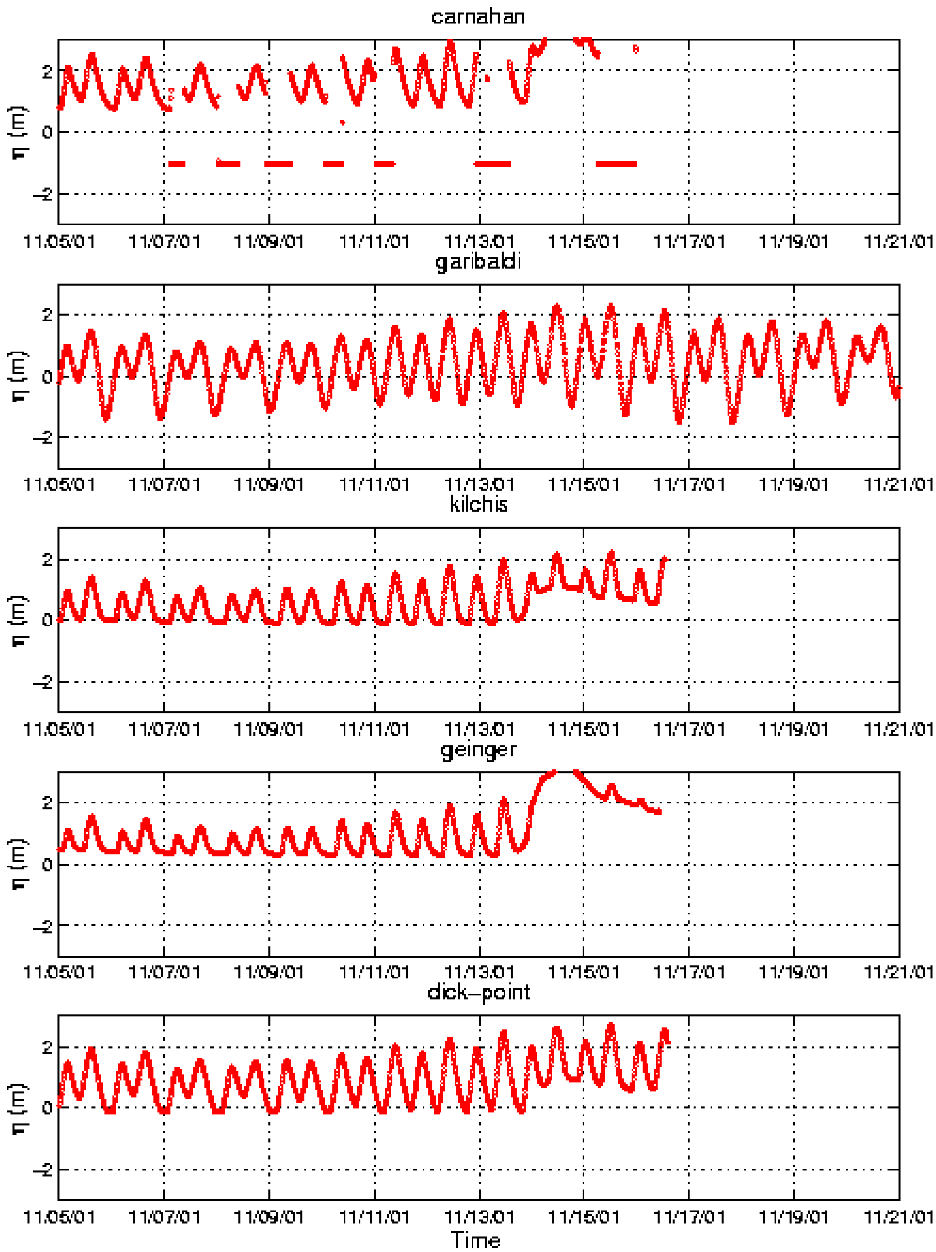

Figure 13: Gage elevation data during the November 14th storm. All the upstream gages stopped working by the end of the storm event.

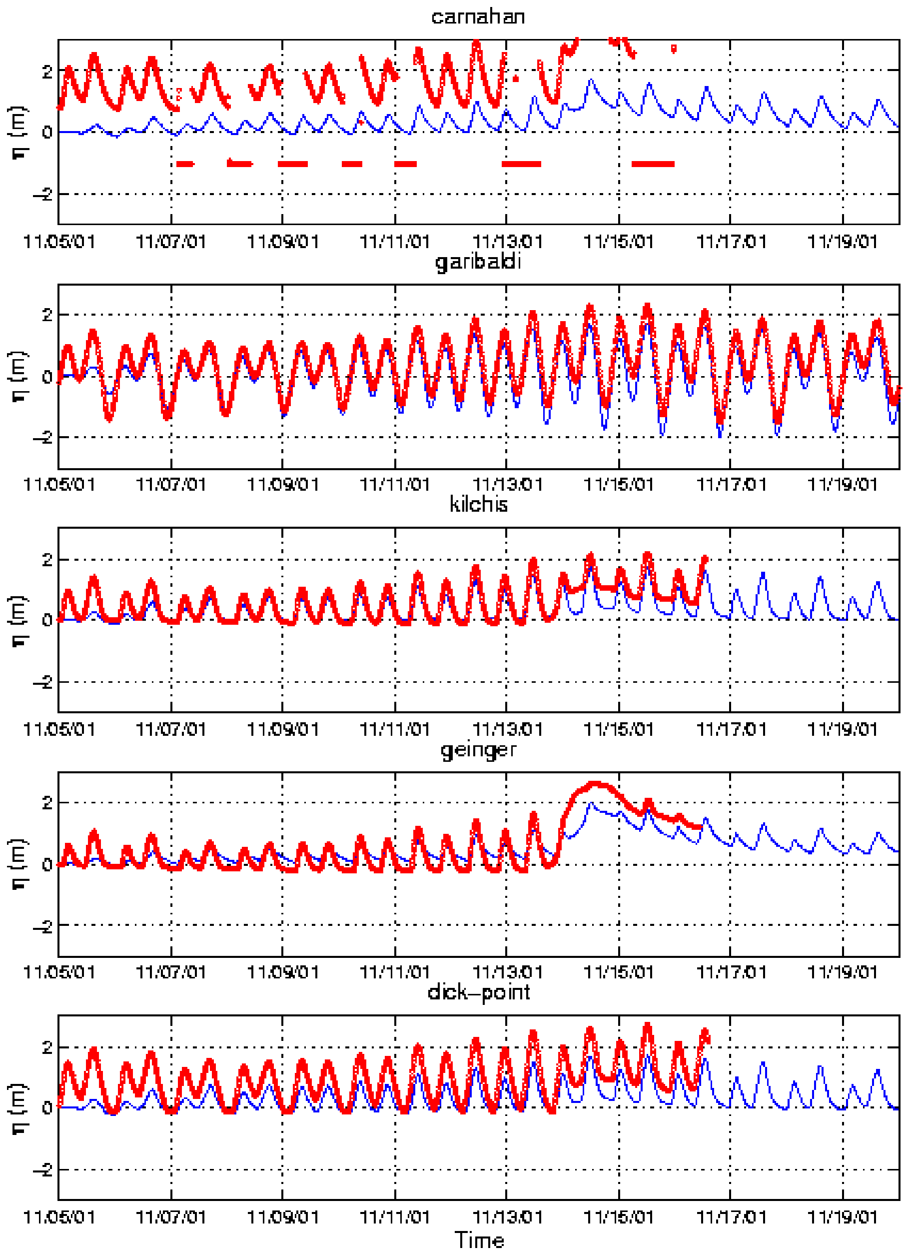

Figure 14: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 1)

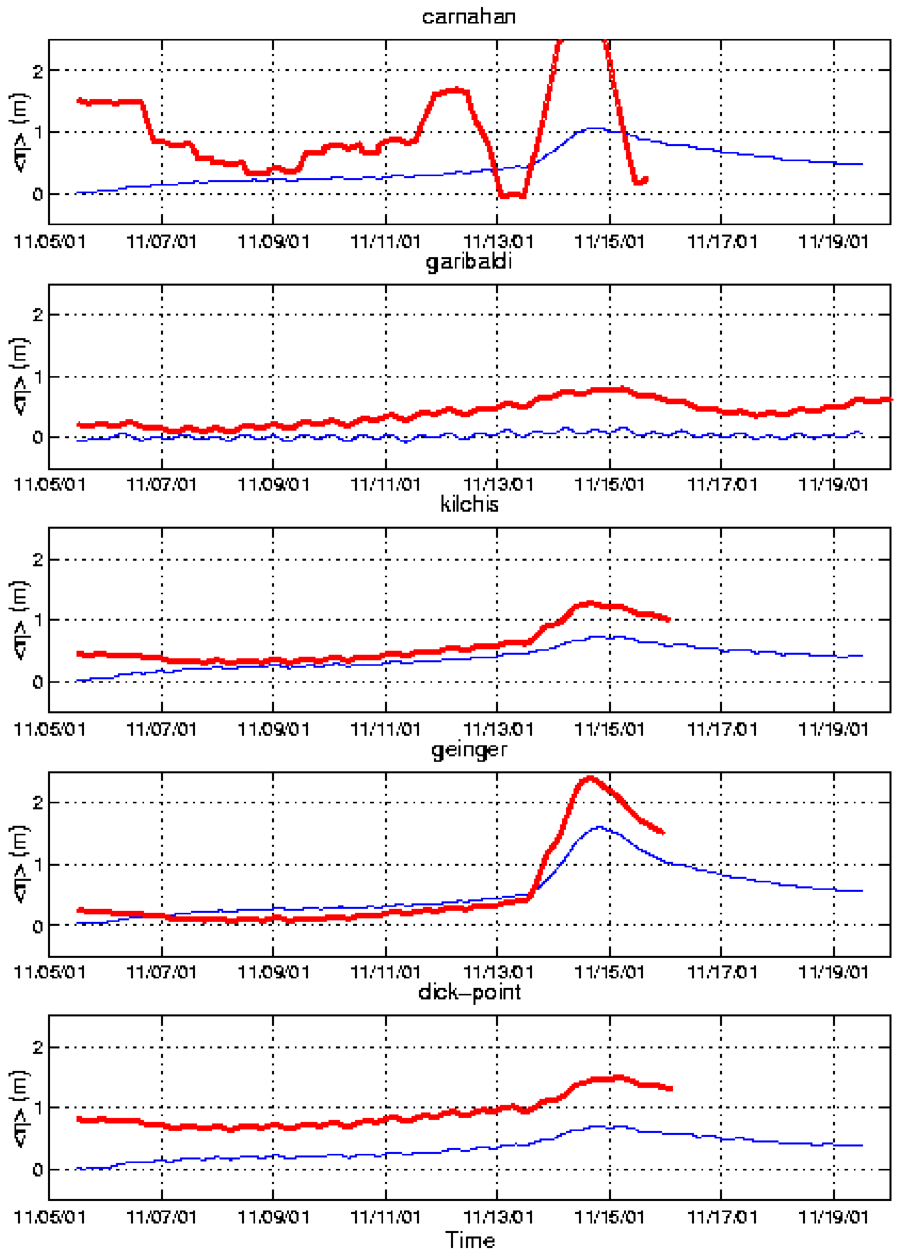

Figure 15: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 1)

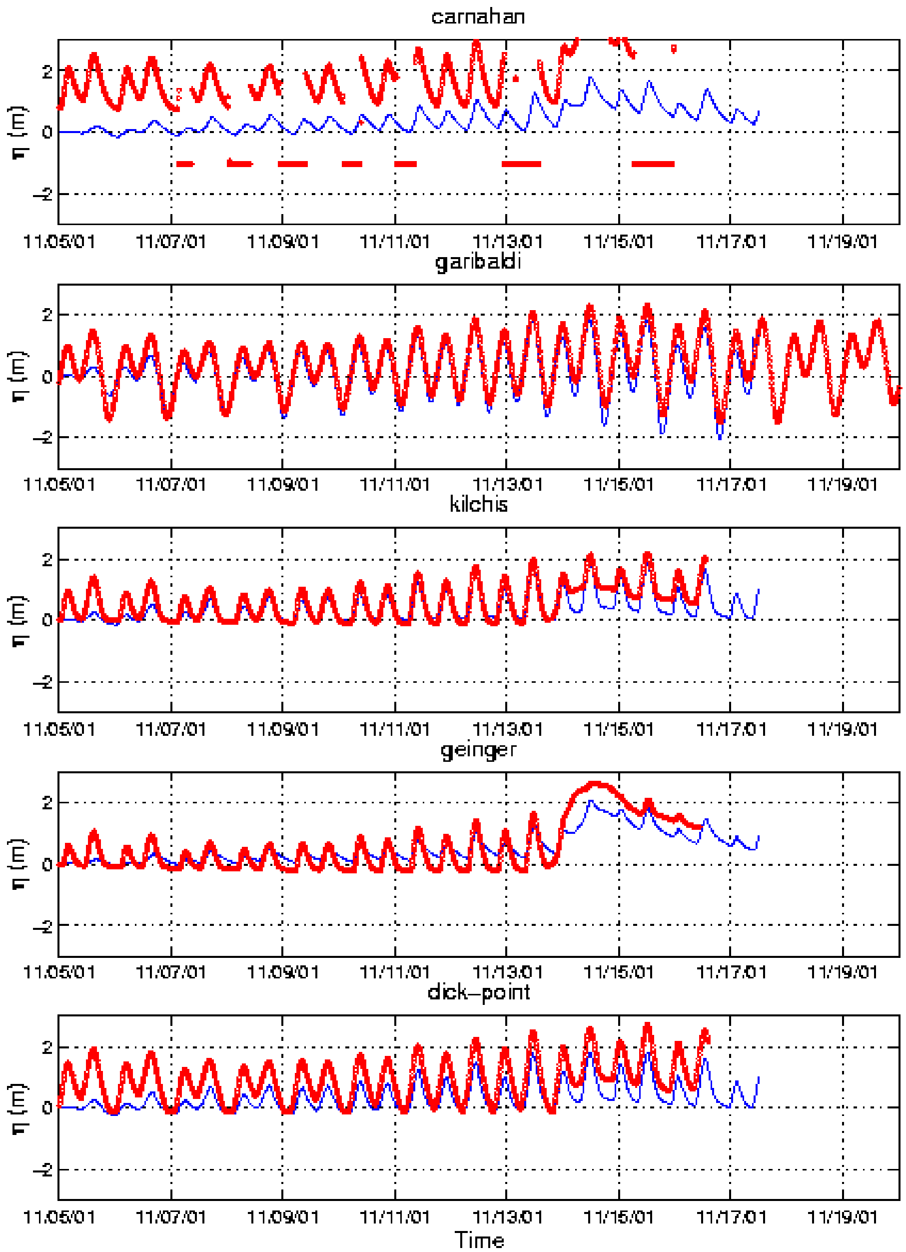

Figure 16: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 2)

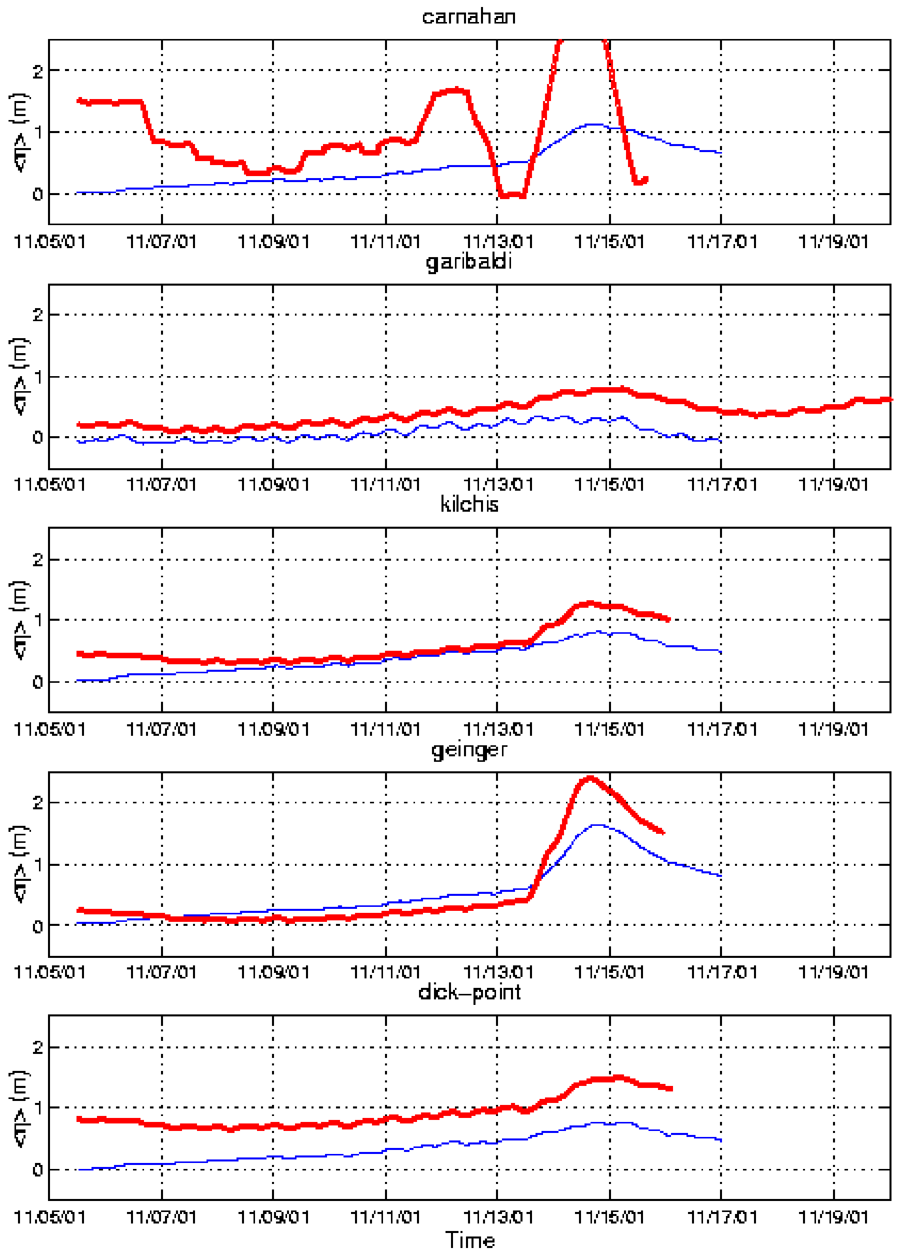

Figure 17: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 2)

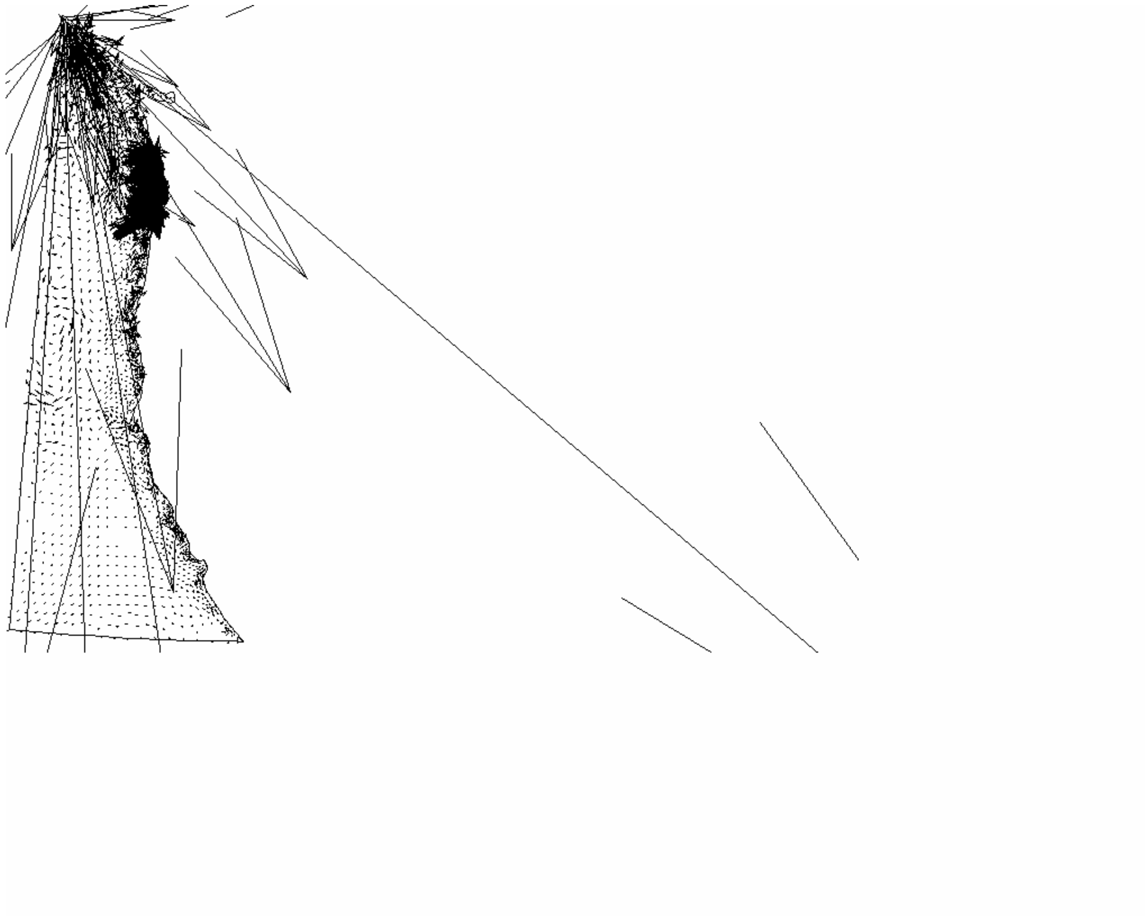

Figure 18: Snapshot of velocities corresponding to simulation in Figure 16. The model blows up at the northern offshore boundary after 12 days of simulation results.

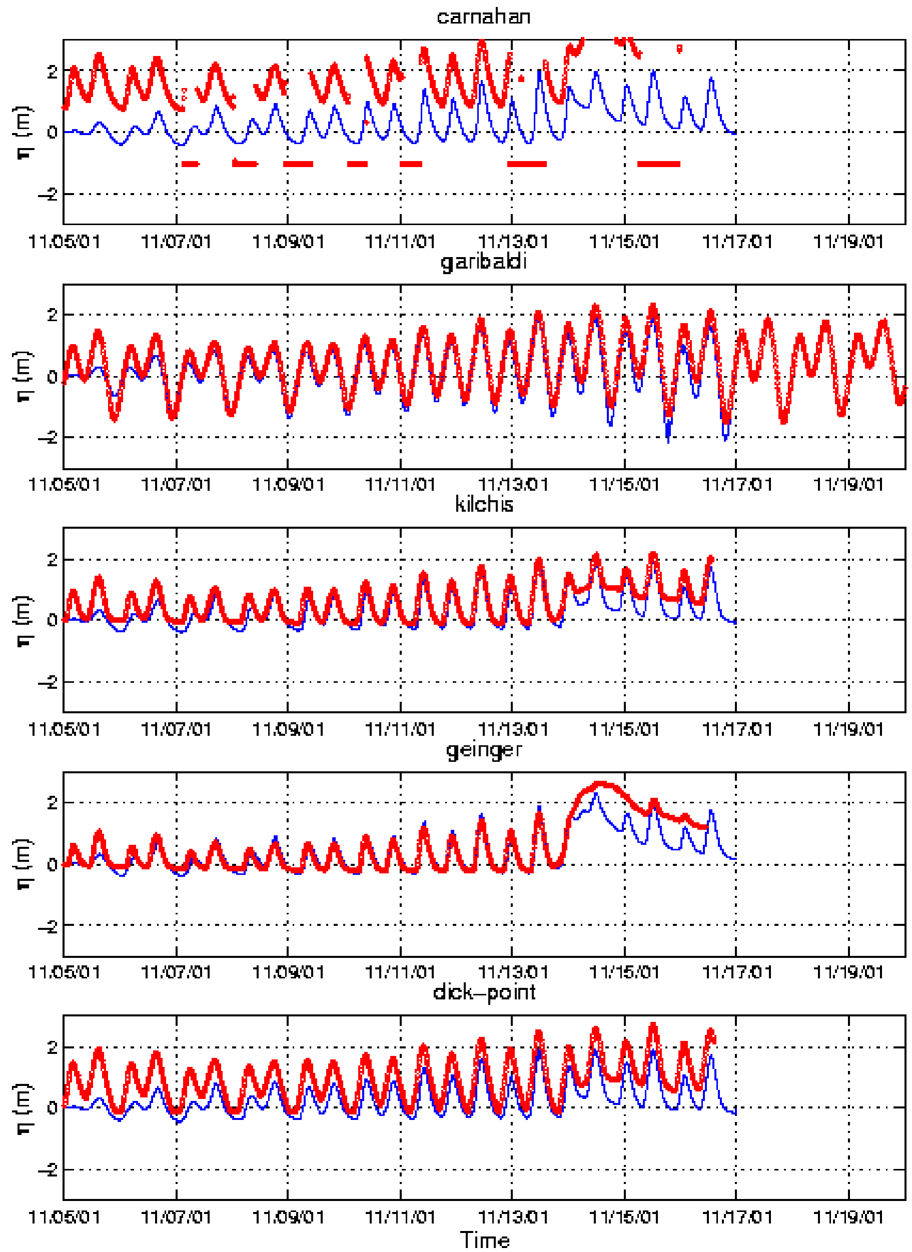

Figure 19: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 3)

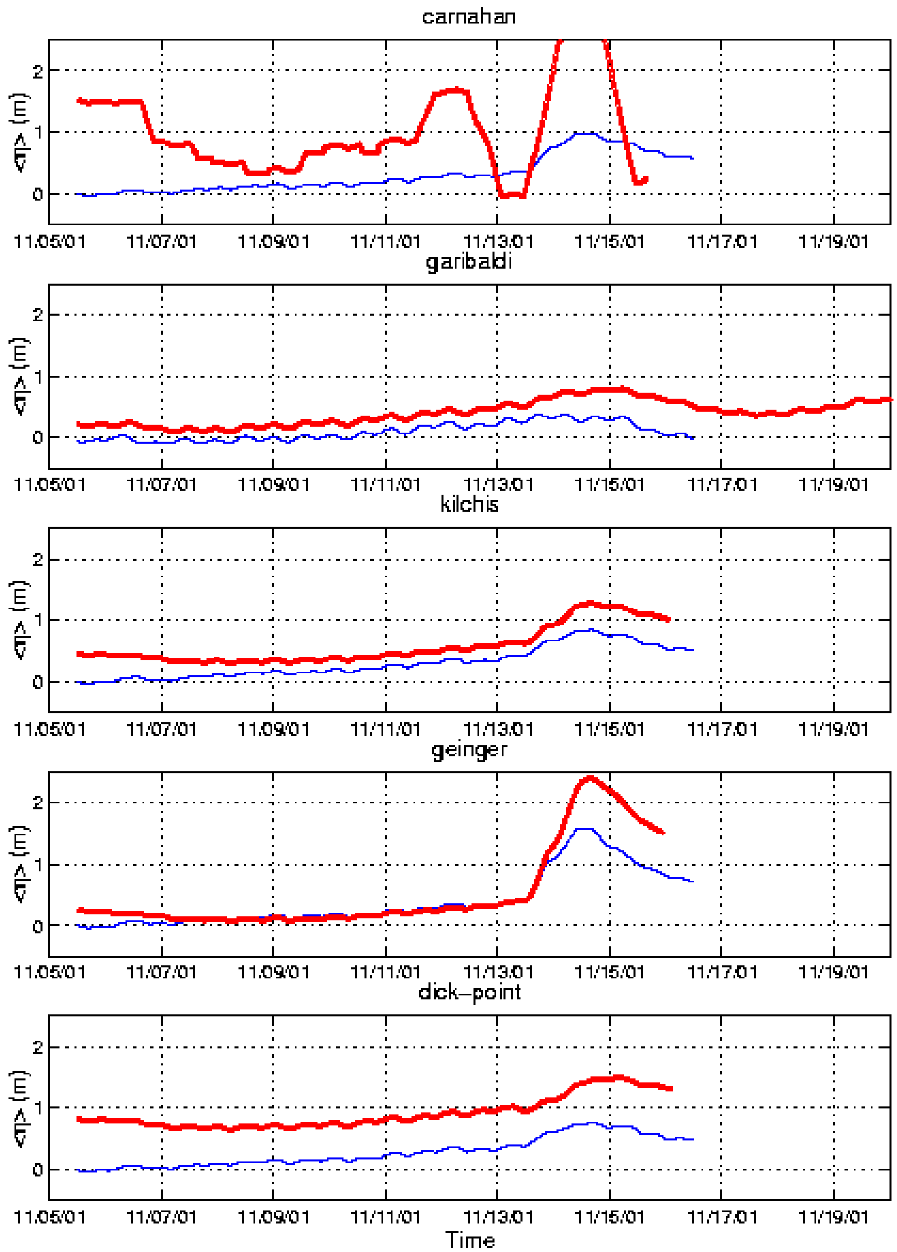

Figure 20: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 3)

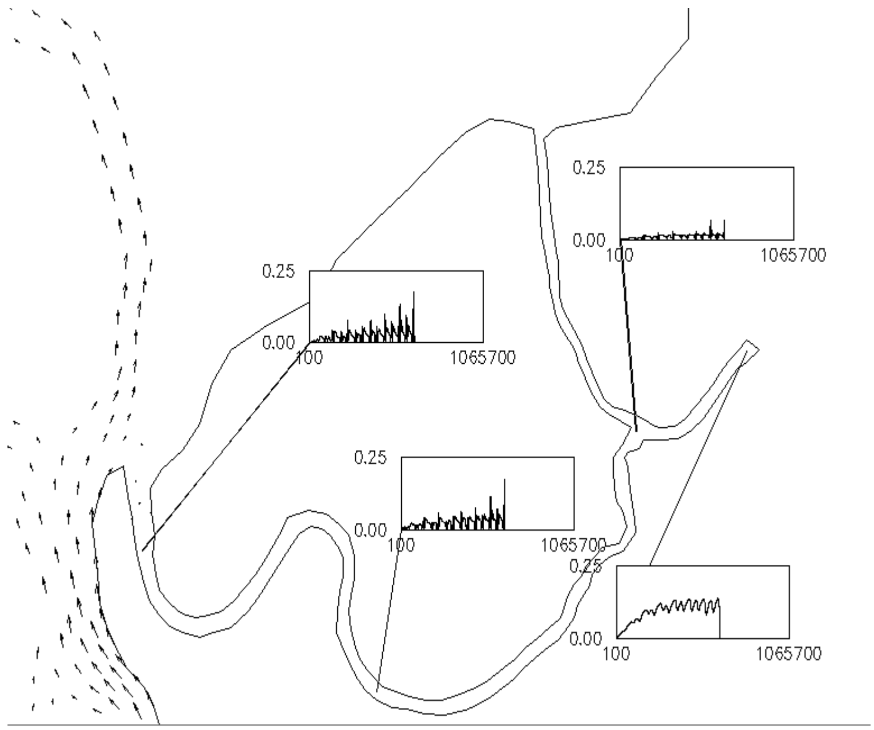

Figure 21: Velocity flow snapshot around the Kilchis river for the simulation shown in Figure 19. Time series of velocity magnitude in m/s at specific locations is shown in inset boxes. The time series plots show the noise in the velocity data and the subsequent drying of the river. The x-axis is in seconds since start of simulation.

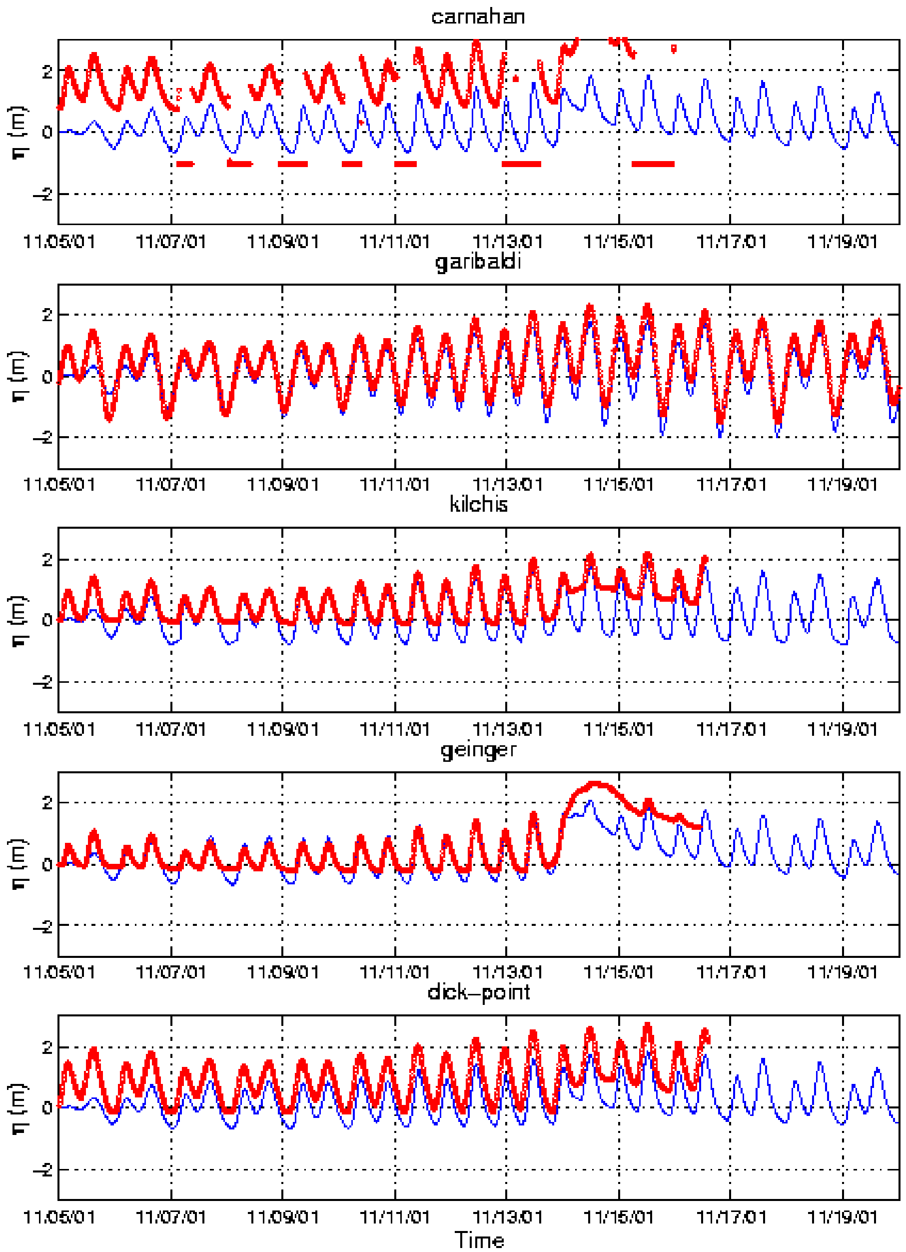

Figure 22: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 4)

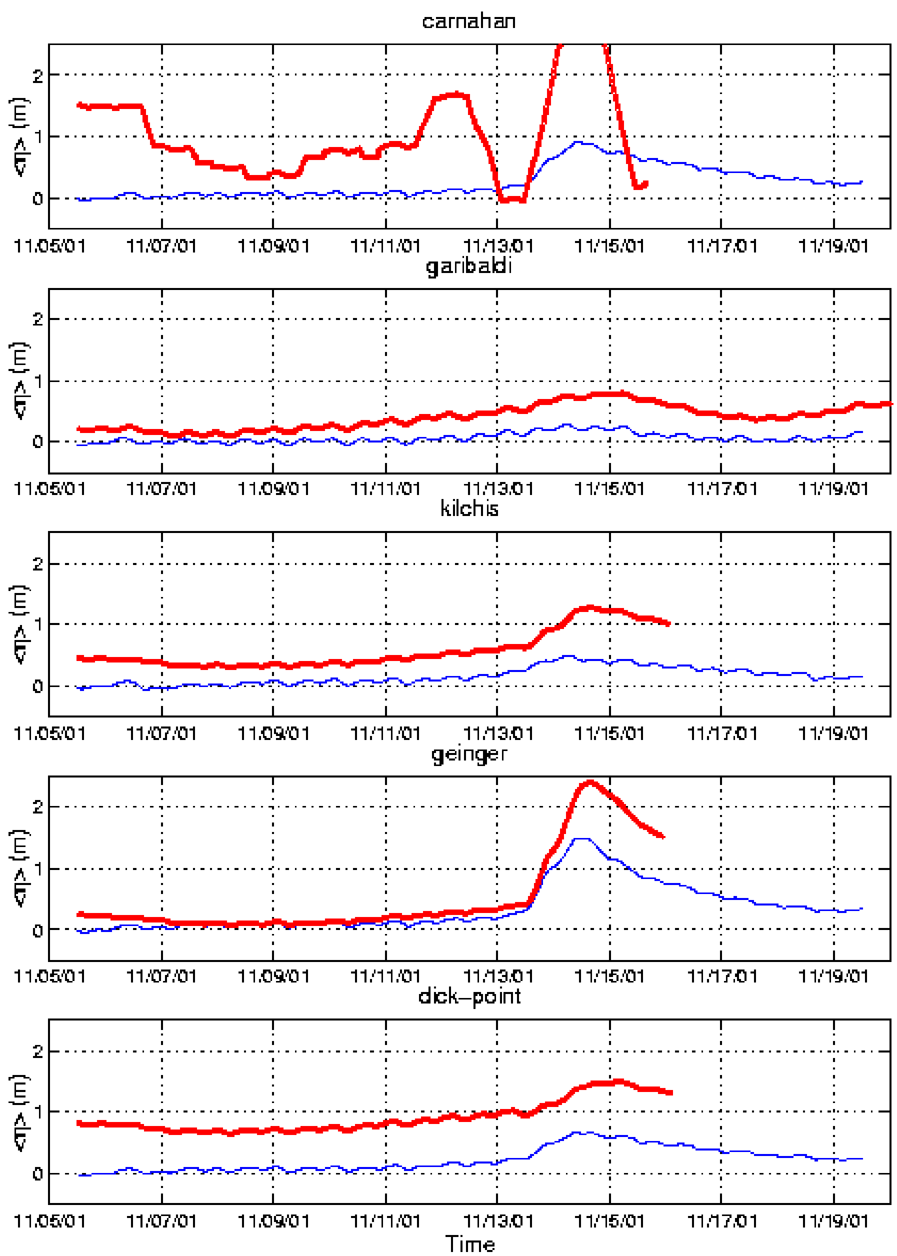

Figure 23: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 4)